The Importance of Biotechnology in the Textile Industry – Natural Textile Dyes

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DEDICATION

Although representing such a small part for the overcoming of the many issues and challenges that affect our society, I can only wish, and hope, this project may be of help to attain a further balanced world… I would like to dedicate this dissertation to Flávio, my youngest brother. Due to his young age, he is, along with the other children and the upcoming generations, the hope for a restored promising future.

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Thank you.

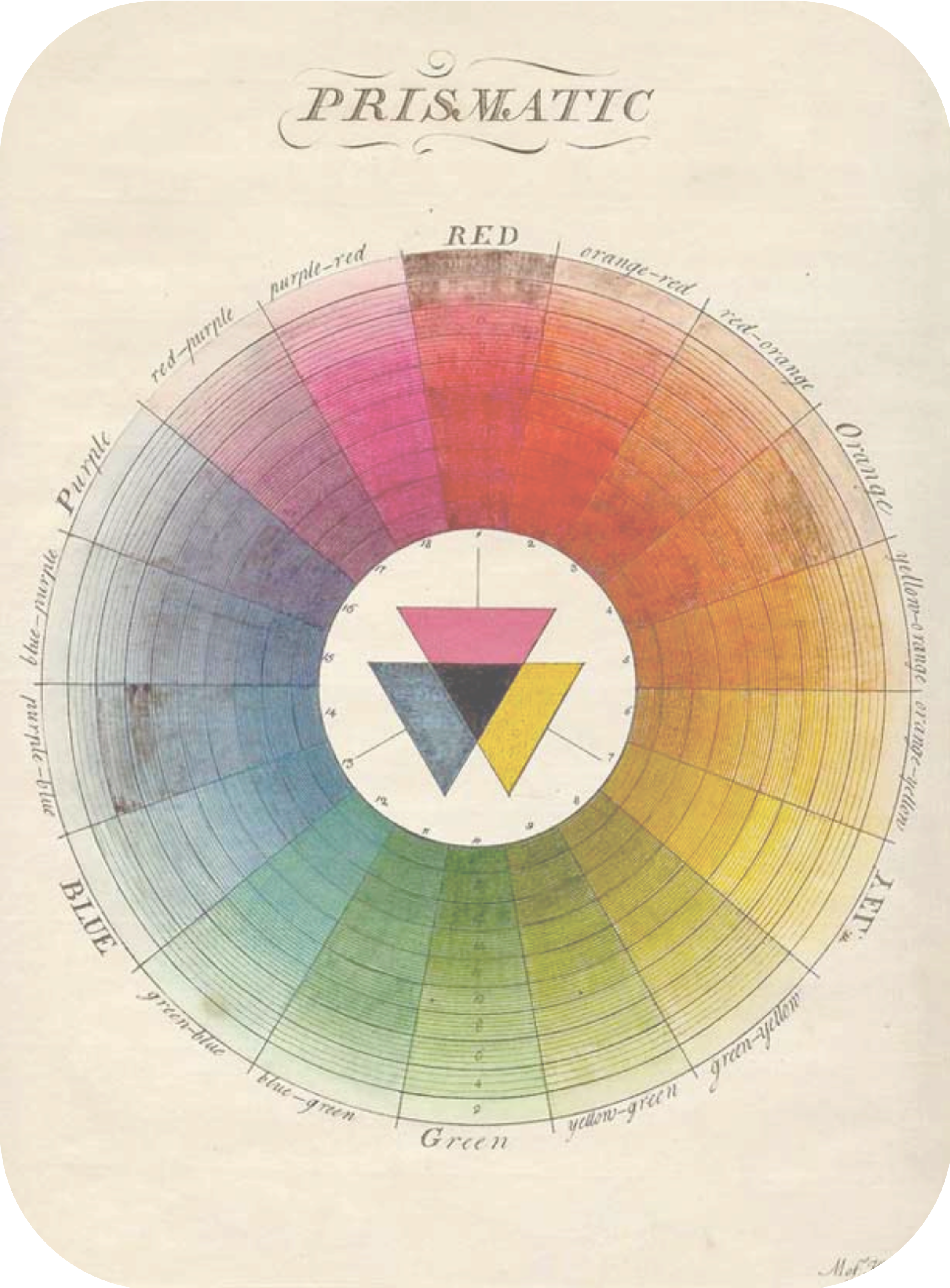

Figure 1 – *Natural System of Colours* (Moses Harris, 1776). This chart was highly influential on those working with colorants because of the detailed approach taken (Royal Academy, 2011).

ABSTRACT

Colour has always been significant in the social and economical context of mankind. It is one of the most important aspects of fashion and textiles, with a remarkable history and evolution. Dyeing process effectiveness is crucial to the textile industry success, attentive on how colours influence consumers. However, dyeing methods are often associated with water waste, fossil fuel generated energy, toxicity and contamination.

The aim of dissertation is to explore and evaluate solutions that could reduce textile industry's environmental footprint by improving the lifecycle product design processes. The solutions in study focus on adjustments to the current production processes, particularly the implementation of biotechnologies to assist the development of a more sustainable method of manufacturing.

This dissertation analyses in detail the textile industrial processes (dyeing) giving special focus to the sustainability aspects of current practices. The main problems of textile industry were analysed: dyeing process, lack of sustainability strategies and consumer's increasing awareness. Alternative manufacturing assisted by sophisticated technologies with a biology-based approach were explored and studied. Responsible design and the use of science in the creative process (product lifecycle) were extensively examined topics, concluding that biotechnological multiple applications are vital and mandatory. Sometimes introducing visionary and radical strategies for improving the performance of products around us, biotechnology presents advantages that help restore the ecological balance, improve social innovation and enhance human wellbeing.

KEY WORDS

Natural dyes; Sustainability; Biotechnology; Biodesign; Innovation; Dyeing process

RESUMO

A cor sempre foi um elemento importante no contexto económico e social da humanidade. A cor é um dos aspectos mais relevantes da industria têxtil e do vestuário com uma história e evolução notáveis. A efetividade dos processos de tingimento é crucial para o sucesso da industria têxtil, atenta ao modo como as cores influenciam os consumidores. No entanto, processos de tingimento são muitas vezes associados ao desperdício de água, energia fóssil não renovável, toxicidade e contaminação.

O grande objectivo desta dissertação é o de explorar e avaliar determinadas soluções que possam reduzir a pegada ecológica da industria têxtil através do aperfeiçoamento do design de produtos e do seu ciclo de vida. Este estudo foca-se, portanto, em eventuais ajustes nos processos de produção correntes, particularmente na implementação de biotecnologias que assistam o desenvolvimento de métodos de produção mais sustentáveis.

A dissertação analisa em detalhe processos da industria têxtil (tingimentos) dando especial relevância às questões de sustentabilidade das praticas correntes de manufacturação. Os principais problemas do sector têxtil e do vestuário foram analisados: processos de tingimento, a falta de estratégias de sustentabilidade e a crescente preocupação e consciência dos consumidores. Processos de produção alternativos assistidos por tecnologias de vanguarda como a biotecnologia foram explorados e estudados. O design responsável e a utilização da ciência no processo criativo (e ciclo de vida de produtos) foram temas examinados extensivamente, concluindo que as múltiplas aplicações de tecnologias de abordagem biológica são essenciais e imperativas. Por vezes apresentando estratégias visionarias e radicais de forma a melhorar a performance dos produtos que nos rodeiam, a biotecnologia apresenta vantagens que possibilitam o equilíbrio ecológico, a melhoria no desenvolvimento social inovador sustentável e o aumento da qualidade de vida humana em geral.

PALAVRAS CHAVE

Corantes naturais; Sustentabilidade; Biotecnologia; Biodesign; Inovação; Tingimento

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ACRONYMS AND ABBREVIATIONS

λ	Wavelength
3D	Three Dimensional
BC	Before Christ
&	Et
E.g.	Exempli gratia
AKA	Also known as
DNA	Deoxyribonucleic Acid
Et Al.	Et alii
Etc	Et Cetera
Fig.	Figure
I.e.	Id est
K/S	Colour Strength
OECD	Organization of Economic Cooperation and Development
OMF	On the Mass of Fibre
TED	Textiles Environment Research
WWF	World Wide Fund for Nature (former World Wildlife Fund)
UVR	Ultra-Violet Rays
Vs.	Versus

GLOSSARY

Term	Definition
Anatomical	Relating to bodily structure.
Bacterium	A member of a large group of unicellular microorganisms which have cell walls but lackorganelles and an organized nucleus, including some which can cause disease.
Biodiversity	The variety of plant and animal life in the world or in a particular habitat, a high level of which is usually considered to be important and desirable.
Bioremediation	The use of either naturally occurring or deliberately introduced microorganisms to consume and breakdown environmental pollutants, in order to clean polluted sites.
Calcium Chloride	A white crystalline salt used to de-ice roads and as a drying agent.
Cellulose	An insoluble substance which is the main constituent of plant cell walls and of vegetable fibres such as cotton. It is a polysaccharide consisting of chains of glucose monomers.
Circular Economy	Generic term for an industrial economy that is producing no waste and pollution, by design or intention, and in which material flows are of two types, biological nutrients, designed to reenter the biosphere safely, and technical nutrients, which are designed to circulate at high quality in the production system without entering the biosphere.
Chromophore	An atom or group whose presence is responsible for the colour of a compound.
Crossbreeding	Produce (an animal or plant) by mating or hybridizing two different species, breeds, or varieties.
Crusades	Each of a series of medieval military expeditions made by Europeans to recover the Holy Land from the Muslims in the 11th, 12th, and 13th centuries.
DNA	Deoxyribonucleic acid, a self-replicating material that is present in nearly all living organisms as the main constituent of chromosomes. It is the carrier of genetic information
Eco-efficiency	Efficiency of an industrial process, etc., in terms of its environmental impact.
Effluent	Liquid waste or sewage discharged into a river or the sea.
Enzyme	A substance produced by a living organism, which acts as a catalyst to bring about a specific biochemical reaction.
Gene Bank	A collection of seeds, plants, or animals, maintained as a repository of genetic material, typically to preserve genetic diversity.
Genetic	Relating to genes or heredity.
Globalisation	The process by which businesses or other organizations develop international influence or start operating on an international scale.
Greeks	Relating to Greece, its people, or their language. Compare with Hellenic.
Hormones	A regulatory substance produced in an organism and transported in tissue fluids such as blood or sap to simulate specific cells or tissues into action.
Insulin	A hormone produced in the pancreas by the islets of Langerhans, which regulates the amount of glucose in the blood. The lack of insulin causes a form of diabetes.
Micro Fibrils	A small fibril in the cytoplasm or wall of a cell, visible only under an electron microscope, and typically aggregated into coarser fibrils or structures.
Microbial	Relating to or characteristic of a microorganism, especially a bacterium causing disease or fermentation.
Microorganisms	A microscopic organism, especially a bacterium, virus, or fungus.
Molecular Biology	The branch of biology that deals with the structure and function of the macromolecules (e.g. proteins and nucleic acids) essential to life.
Molecule	A group of atoms bonded together, representing the smallest fundamental unit of a chemical compound that can take part in a chemical reaction.

Nucleotides	A compound consisting of a nucleoside linked to a phosphate group. Nucleotides form the basic structural unit of nucleic acids such as DNA.
Plasmid	A genetic structure in a cell that can replicate independently of the chromosomes, typically a small circular DNA strand in the cytoplasm of a bacterium or protozoan. Plasmids are much used in the laboratory manipulation of genes.
Polyester	A synthetic resin in which ester groups link the polymer units, used chiefly to make synthetic textile fibres.
Precipitation	The action or process of precipitating a substance from a solution.
Proteins	Any of a class of nitrogenous organic compounds which is have large molecules composed one or more long chains of amino acids and are an essential part of all living organisms, especially as structural components of body tissues such as muscle, hair, etc., and as enzymes and antibodies
Rhizosphere	The region of the soil in contact with the roots of a plant. Narrow region of the soil that is directly influenced by root secretions and associated with soil microorganisms.
Romans	A citizen or soldier of the ancient Roman Republic or Empire.
Urea	A colourless crystalline compound, which is the main nitrogenous breakdown product of protein metabolism in mammals and excreted in urine.

1. Introduction

1.1 Research context

Waste, water contamination and the use of fossil fuel generated energy are major issues of modern society. The textile industry is a powerful sector economically however, unfortunately, it is also one of the most pollutant industries on the planet. Common non-sustainable issues are mostly associated with finishing processes, such as dyeing (Fletcher, 2008).

Colour is a vital factor for the commercial success of textiles and fashion design products. Therefore, dyes' production and application are indispensable processes within the industry. Nevertheless, effluents from textile dyeing processes are responsible for a high level of toxicity and water contamination, when not conveniently treated before being thrown into natural pure waters; these represent a massive threat to the health of both consumers and textile workers as well as to the environment, affecting with great impact all ecosystems (Vandevivere, Bianchi, & Verstraete, 1998; Greenpeace, 2011). In order to reduce the environmental damage of the textile and apparel industry, without compromising its effectiveness and success, alternatives must be discussed.

Sustainability strategies in several varied fields are often assisted by biotechnology. Biotechnology applications are vast and increasing, playing a key role in reducing ecological footprint of industries, particularly in the last decade. Technologies using bioresources are not new but the improvement of science has made their potential immeasurable. The application of biotechnologies in the textile industry may be, similarly, significant, particularly in the development of sustainable products - improved methods of manufacturing, smart materials, responsible goods - which lifecycle enables for the enhancement of quality life and reduced ecological burden. The improvement of varied species of plants to produce fibres, management and treatment of waste and effluents, manufacture of fibres and natural ancient dyes, etc., are amongst the most known forms of biotechnology applied to the textile sector. The latter example (production and application of natural dyes) is a fundamental subject of analysis for the industry and for this study. Along with increasing awareness of consumers regarding the lack of sustainability in the textiles' current processes of production (Bendell & Kleanthous, 2006), a revivalism of ancient dyes has been noticed, as opposed to the synthetic ones that are usually employed in general textile dyeing. Ancient dyes represent a sustainable alternative; they are perceived as less dangerous due to their biodegradable nature and high level of compatibility with the environment, hence, safer to dye with, to be used when wearing textile products, no contamination, etc. However, both type of dyes – synthetic and natural – have advantages and disadvantages. These need to be carefully investigated from a sustainable and responsible perspective so to guarantee high quality design.

Sustainable design landscape, we believe, may be shaped through the possibilities offered by science (through sophisticated technologies) applied to the creative process, when projecting textile products or materials and contemplating their lifecycle. Dyes are essential elements of textiles and exceptionally significant type of material that should not represent danger to consumers or the environment. The relationship between biotechnology and design is therefore subject of greater consideration, analysis and debate throughout this dissertation. Moreover, it is of great importance to discuss how it impacts the world and what it represents for both consumers and industry and their different needs, demands and expectations. Understanding the real advantages and disadvantages of biotechnology application will, confidently, help to map a new perspective on sustainable strategies available for industry whilst designing products, particularly regarding textile dyes and dyeing methods.

1.2 Aim of investigation

The present study is a continuous work following the masters' degree dissertation that had Design and Biotechnology as central subjects of analysis and discussion. The core focus studied was the sustainability of the textile dyeing industrial processes by understanding the evolution of such materials throughout the centuries – from ancient times to the current century. Several subjects were identified as vital to the study such as different symbolical and social meanings of colours, dyeing history, biological resources, provenience, technologies involved, etc. Despite being one of the most important materials in the world, representing such a big industry as the textile sector, dyes' production and application are considered problematic when debating the sustainability topic.

This new century is characterised by many challenges, especially for the textile industry (and for designers). It has to deal with the economic downturn threatening sales and a growing awareness of real social and environmental challenges, such as climate change, wars over resources and increasing consumer expectations of brands. Sustainability issues are not only about resources exploitation anymore but rather working with an ever-changing and competitive society, with companies which budgets are low or with divisional problems, and so on. As a result, research and sustainable development strategies must be highly focused since the challenges will force many transformations in the sector.

Dyes industry, both production and application, are often associated with waste, fossil fuel generated energy and water contamination, therefore representing a threat to the environment and consumer health. The search for sustainable alternative strategies is imperative; the present project focuses on the most important aspects of dyeing and the understanding on how materials behave and which technologies might be used to reach a further satisfactory and sustainable stage of production since the current methods of manufacturing reveal little effective, failing to acknowledge the balance of the ecosystems. The analysis of these subjects will also question responsible design and technologies' negative and positive impacts in our daily lives. With this research, it is intended to question, test and propose a different methodology regarding the production and application of coloured materials in textile products (and on an industrial level). As a design study, the main questions and objectives are centred in the creation of sustainable and effective products analysing their lifecycle as well as their materials, in this case, textile dyes. Responsible sustainable design should neither comprise, nor tolerate, materials that are not safe for consumers and the planet, damaging ecosystems. In contrast, it has to "create conditions conducive to life" (Benyus, 2002).

Therefore, the motivations behind this study emerge from the determination to question the current applied methods and reconsider creative processes. All scientific research and endeavours in the creative process are driven by the desire to investigate and develop sustainable systems of manufacturing allowed by the merging of science (particularly biology-based technologies) and design. The aim of this dissertation is to adjust responsible design with consumer demands and industrial success, contributing to the consideration and understanding of challenging, complex and urgent matters within the textile industry and current sustainability issues. In addition, after bibliographical research, it was noticed that, albeit extensive literature, the related topics were not efficiently examined in greater detail.

This study expects to demonstrate the importance of certain biotechnologies as an approach to new viable strategies of sustainable development and the creation of responsible products that enhance and improve life in general. Simultaneously, by shedding light on the related subjects, it is anticipated that this research will raise awareness providing knowledge in regards to dyes and processes involved, as well as alternatives to consider. After surveying all of the key elements, it is believed this project will offer a larger picture on the external pressures being exerted on the fashion/textile industry and reveal methods that can satisfy outer demands whilst establishing practices that are resilient and effective.

1.3 Statement of the problem

Research debates relate biotechnology and design through a more comprehensive study on sustainability, as opposed to the current textile production processes in regards to textile dyes, considered non-sustainable. Aspects of the research involve contemplating the following questions:

- How will bio-based technologies affect the textile industry, regarding dyes and methods involved? How will they evolve?
- How will biotechnology impact when designing responsibly? How can living-technology influence on how we design, manufacture and experience our lives?
- What are the possibilities of new manufacturing methods and innovative materials?
- How can science and design, merged as one, create the condition to generate products that enhance lifestyle and promote wellbeing? How will they impact and shape the world?

Regarding the question of investigation of this research, the statement of the problem is as follows:

- Biotechnology is the key for the application of natural/bio dyes in an industrial scale, simultaneously guaranteeing a more sustainable development in the textile and fashion design field.

1.4 Methodology

In the first stage of the study, and aiming to complement previous literature review (State of the Art), extensive bibliographical research (e.g. scientific papers, books, case-studies) proceeded by crossing different fields of knowledge (e.g. history, design, biology, anthropology, chemistry), vital to the problems' context and interpretation and further analysis. This helped to assess and deepen knowledge on the co-related key concepts; thus allowing for the contemplation and discussion of the following elements in consideration:

- How can the environmental footprint of textile production be reduced
- Identification of varied biological resources, technologies involved and their effectiveness
- The role of sophisticated technologies in providing a range of services to textile and fashion industry
- New design methodologies and the symbiotic relation science/design
- How can materials enable for a more sustainable future
- Advantages, potential and impact of biotechnology

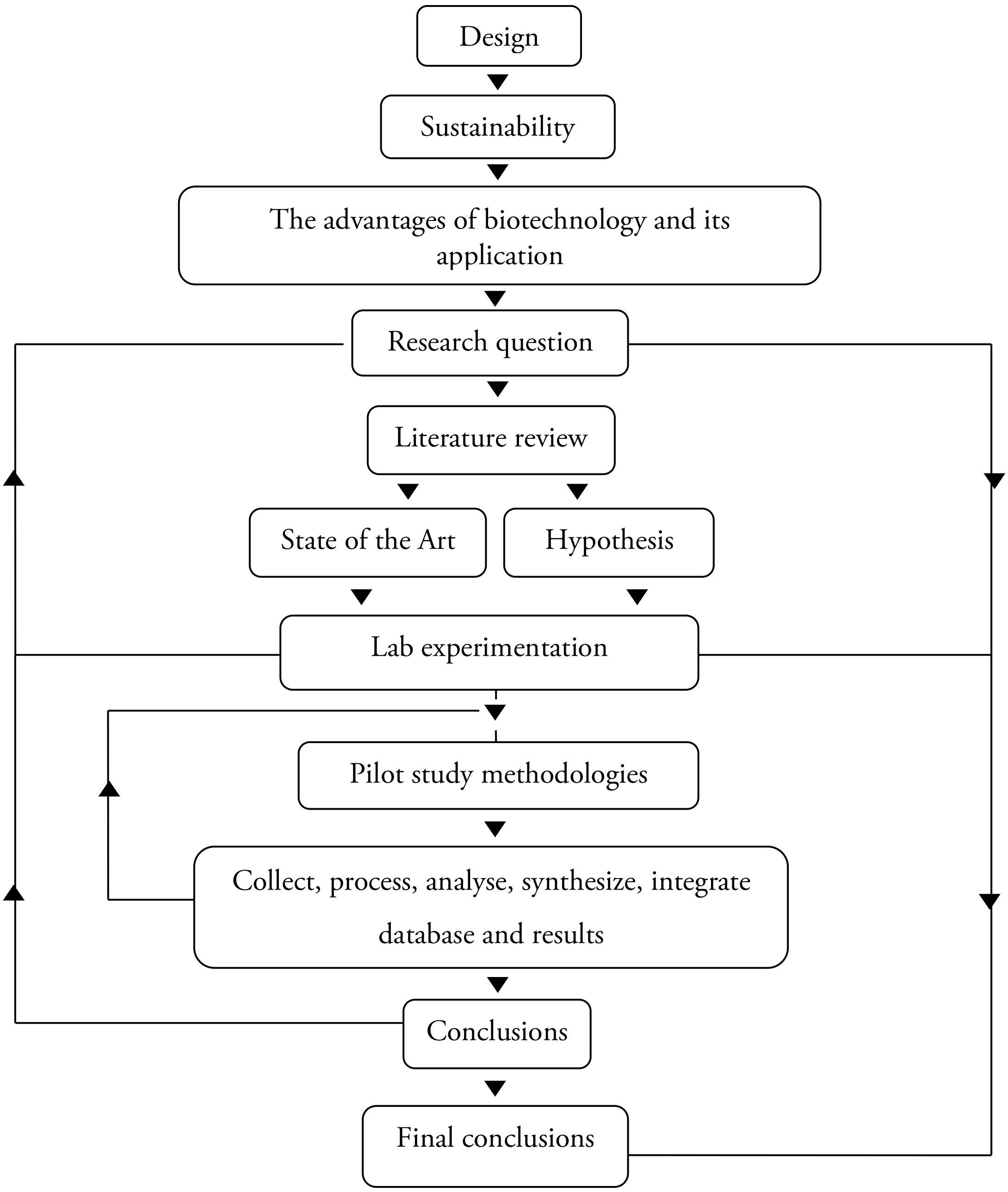
Image research is proved equally significant, crucial for a broad understanding of the explored content, illustrating data that translates relevant information on what is intended to exemplify.

In the first stage of research the type of methodology adopted allowed for the collection, overall assessment and filtering of the essential data, a relevant activity so that the approach to the investigation problem could start taking shape (constantly taking into account the study purposes). This process proved vital to bridge this part of the study to a second phase of research, where laboratorial experiments needed to be conducted. In regards to the second stage of research (practical part of this project), experiments were conducted with the collaboration of the University of Leeds, School of

Design (United Kingdom) and the methodology applied was, essentially, interventionist and quantitative, conducting experimental work, imperative for the understanding of what was intended to prove.

1.4.1 Research Design

Table 1 – Research design for the study



1.5 Thesis structure

The structure of the present dissertation suffered several transformations throughout the whole research process. This occurred whilst processing all analysed data (acquired or deepened), which was getting collected and organised as the study unfolded, during all this time.

At the cognitive level, the attempt to optimise this structure was a real challenge; the ideas, concepts, uncertainties, hesitations, updates, etc., made it hard, at times, to carry the effort to build and improve this structure in a more coherent, solid, definite, (and clear as possible) research study.

The following chapters mirror the varied stages of the research related methodology process, intending to organise all the gathered and managed data. Thus, and aware all research work is not comprehensive at a quantitative level (as it would never be), this study was mainly shaped for the general understanding of the context and for the analysis and interpretation, of what is believed to be transmittable and excellence knowledge.

The first chapter – Introduction – contextualises the actual study and its central objectives as well as the research statement (hypothesis) and related methodologies.

The second chapter – Textile dyeing – presents (in a very concise way) the general dyeing processes, their purposes and consequences, analysing simultaneously what it entails both to the environment and consumers. At times supported by ethnological or archaeological examples and case studies, several dyes, dyeing methods and technologies involved are described and elucidated. These subjects were addressed in a historical/evolutionary approach, equally revealing eventual changes throughout the eras. Still in this chapter, biological resources were also contemplated; this part introduces different types of bio resources (ancient dyes) possessing great dyeing potential properties. The colouring compounds are described according to their name, provenience, technologies, etc. The fundamental understanding of natural dyeing processes is mandatory to relate concepts contributing to a further effective sustainable progress. Therefore, this chapter includes detailed data on natural dyeing procedures and related techniques.

The third chapter – Biotechnology – emerges as an analysis of the technological innovations and evolution, relating classic and modern technologies that use biological resources. Through the analysis of case studies, subjects are described and debated to better enlighten the advantages of biology-based technologies in assisting to unravel sustainability related issues, particularly in the textile dyeing industry.

The fourth chapter – Sustainability – discusses the role of design in shaping a further sustainable landscape in the present context of varied pressures defining society, industries and consumers. Subjects such as sustainability, industry and consumer demands are addressed and analysed, considering simultaneously the extant alternatives for the improvement of sustainable strategies and ecological footprint reduction. The recent trend of science appropriation by the design creative process (and industries) is also considered and examined, extensively, through the investigation of several case-studies exploring the potential of biotechnology.

The fifth chapter – Sustainable dyeing – considers the alternatives for a further responsible designing process or manufacturing of products. As essential materials to the development of textile products, alternative textile dyes are discussed. This chapter also refers to the practical part of this study, which consists of the evaluation of a bio-dye and its effectiveness towards a further resilient, improved dyeing process.

The sixth chapter – Conclusion – highlights and relates all the previous topics and their main points of criticism. Additionally, it points out some related issues introducing eventual relevant aspects for a future study.

2. Textile Industry

2.1 Textile dyeing processes

Colour always had major importance in the humankind history for varied different reasons (e.g. symbolical, social meanings) and observable in many rituals of war, religion or aesthetics. One is surely conditioned to react to colour in both emotional and psychological ways (Appendix F). Along with the different societies' development, the need for colour production emerged and evolved, firstly applied to the body and, later on, its extension – clothing. To produce the colours spread all over nature, many coloured compounds were discovered through technical experiments, or simply by accident, throughout history. In the ancient times these dyeing compounds were mainly obtained from natural sources like plants and animals.

Figure 2 - Tribal by *Herring & Herring* (Design Scene, 2009).

Despite the infinite amount of coloured substances found in nature most of these do not qualify as dyeing material, simply because they do not guarantee a quality dyeing in terms of fastness (i.e. this class of substances not always provides for the ideal fixing conditions so that the bonding of the chromophore to the substrate may occur). Unless grasped appropriate knowledge related to the chemical and physical properties of both dye and fibre as well as associated dyeing processes of application (amongst other) the colour will eventually fade or bleed from the fibre during usage, light, perspiration and washing.

However, some colouring compounds obtained from nature may deliver great quality dyeing, again, once certain techniques involved are understood. In the Ancient times, the knowledge on several different technical elements related to dyeing and biological resources in use, quickly represented an economical aspect of value. With a deeper understanding on how to manipulate certain colouring matters and their application onto fibres, dyes and its industry achieved superior significance in the social and economical context of mankind throughout history. In regards to the economical weight of certain specific dyes, Greenfield (2005) asserts the importance of cochineal in her book *A perfect red: empire, espionage, and the quest for the color of desire*, where she describes the stories related to the chase of a red dye surrounded by mystery due to their, rather remarkable, dyeing properties and economical value, believed to have contributed massively to the wealth of the Spanish Empire. According to the author, after its discovery in ancient Aztec markets by the Spaniards, in 1519, the Spanish monopoly of cochineal dye was a significantly worthy fortune; the mystery surrounding its biological resource and dyeing techniques was the cause for one of the biggest chases in history lasting for more than three hundred years. Everyone (i.e. pirates, explorers, alchemists, scientists, and spies) joined the quest for the understanding of this red-producing dye (Greenfield, 2005).

The power of colouring matters resides in the deep understanding of intricate and complex chemical and physical interactions between dyes and fibres. Besides the pattern/printing, consumers demand for basic characteristics in textiles: high level of colourfastness regarding light, washings and perspiration. This is the backbone of dyeing and the aspect that distinguishes a great dyeing from a poor one, as mentioned above. In order to guarantee stable and uniform colour shades (colourfastness properties) throughout the substrates, the substances conferring colour to fibres must present high affinity with these, creating a permanent bonding (Clark, 2011). These are factors depending on the substrate texture or composition as well as on treatments applied previously or after the dyeing process (Clark, 2011; Malik, Ghromann, & Akhtar, 2014).

Regarding the art of dyeing and its evolution, there is a very limited amount of information that can guarantee, accurately, methodologies and dates. According to Edward Bancroft (1814), the little knowledge preserved by the Greeks and the Romans, (acquired from other cultures with whom they interacted or via the developments in their own dyeing industry) was lost around the 5th century (probably along with the consecutive acts of destruction of the Ancient Library of Alexandria or due to the numerous amount of expertise lost along with the people affected by the plagues). The remaining scarce information on dyeing techniques remained in Italy and was sporadically improved by the Greek artists who learnt from the East, as a result of the Crusades, or from the Venetian importations (oriental artefacts). Italy is, thus, considered the place where the dyeing industry began. Further expertise was enhanced by new techniques and methods of production coming from Asia and, later, America or eventual new acquaintances on the developing chemistry field. The varied dyeing processes became superior in quality and rapidly spread through Europe (Bancroft, 1814).

Regarding methods of extraction and dyeing techniques, Bancroft mentions that the first reports, albeit incomplete, derived from Venetia in 1429, covered in a book named *Mariegola dell' Arte dei tentori*. Aware of the limited amount of data contained in this book, and to boost the dyeing business, an additional book was written in 1548 – *The Plictho.* This is a compilation book on dyes and dyeing application techniques with information gathered from different regions of Italy and other countries. As discussed by Bancroft (1814), this was the starting point from where the art of dyeing was improved; the author also refers that from all the dyeing substances reported on in *The Plictho,* the Cochineal or Indigo dyes were not cited, meaning that most probably these dyes were not yet applied in the Venetian's dyeing industry at the time (Bancroft, 1814). In regards to the cochineal dyestuff not being used by the Venetians, it makes perfect sense since, as a bioresource native to Mexico, it was only discovered by the Spaniards (just prior to the writing of *The Plictho*), who, as cited by Greenfield (2005), detained the cochineal monopoly for over three centuries. Concerning the non-usage of indigo by the Venetian dyeing industry, this might be due to the dye related dyeing procedures, which were not yet fully understood; the expertise on dyeing procedures and mordents involved were somewhat difficult to grasp. According to Bancroft (1814), only two centuries later is Indigo referred to, in a Dutch book translated from Flemish by Thomas Purfoot - *A Profitable Booke, declaring divers approved remedies to take out spots and stains, in silkes, velvets, linnen and woollen clothes; with divers colours how to dye velvets, and silkes, linnen, and woollen, fustian, and thread: also to dress leather* and *to colour felles*. This book contains information on techniques applied on the Flanders dyeing industry, which was thriving exponentially at the time (Bancroft, 1814).

Currently, with the advancements of science, one can rely on different methods that help to assess, understand and rebuild the complex dyeing process history. Varied chemical analysis can be applied to archaeological artefacts which helps to identify and comprehend which dyeing methods might have been applied, what type of mordents may have been used and which existing chromophore can be found in the fibre. They also allow for the possibility of learning about the biological resources in use, their origin and date (Fiore, Parera, Orquera, & Piana, 2008).

Additionally, the many answers provided by excavations and archaeological findings may enable for the reconstruction ancient peoples' lifestyle and customs, i.e. the discovery of a certain dye does not only signify its eventual data or grasping the chromatic preferences and symbolisms of certain cultures but, rather, expose facts on the cultural, commercial and technological transactions of specific periods in time, fundamental to the general understand of the world. The contribution of the knowledge on dyes availability and dyeing processes involved (production and application) may be key for finding alternative solutions for the eventual issues our society faces currently, in particular the textile industrial challenges (as analysed later on in this dissertation).

Dyes continued to be quite limited throughout the medieval time until the 19th century. William Perkin discovered, in 1856, a coloured compound (mauveine) producing a very stable colour, which led the way to the development of further synthetic dyes. This advancement in the chemistry field changed the textile and fashion world by pushing away natural dyes from the market (along with their characteristic lengthy and difficult associated processes and their prices, comparatively, too high) and providing for an infinite range of colours, easy and cheap to produce. However, despite the many advantages presented by synthetic dyes, their production and usage are the cause of one of the major sustainability issues the textile industry is currently facing (Fletcher, 2008; Greenpeace, 2011; Greenpeace, 2012).

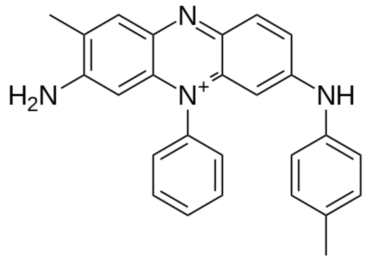


Figure 3 - Mauveine chemical structure (Wikimedia Commons, 2014).

As an ancient art that started millions of years ago, the dyeing industry evolved to a great extent. Dyes commercial availability is enormous and their process is one of the most fundamental aspects of the textile industry commercial success.

In regards to coloured textiles, the most important requirements are the ones related to colour uniformity (colourfastness); dyed materials must possess exceptional resistance to agents that cause colours to fade, such as usage, light, repeated washing and perspiration. To guarantee the colourfastness properties, the substances conferring colour must possess an extraordinary level of affinity with the fibres, to offer colour uniformity and stability. Dyes must also be economical and available in high quantities (Clark, 2011). The higher demand for these compounds originated the synthesis of many millions of dyes in the past century. There are over two thousand different types of dyes in the textile industry alone, a justified amount since each type of fibre to be coloured requires dyes with specific characteristics (Zollinger, 1991).

2.2 Chemistry of textile dyeing

Dyes represent a massive industry; aware of the influence of colour over consumers (Appendix F), the textile and fashion industries explore this aspect in great detail, spending massive amounts of energy and money in the pursuit for the perfect colour. This is crucial so the product projects an intended message to increase sales (Davis, 1992;

Scully & Cobb, 2012). Dyes commercial availability is enormous and their process is one of the most fundamental aspects of the textile industry's commercial success; these must be economical, available in high quantities and in diverse shades of colour. The higher demand for these compounds originated the synthesis of many millions of dyes in the past century (Clark, 2011).

The stability of colours is, indeed, one of the most significant requirements in the textile sector and a subject characterised by an extreme complexity. As already mentioned, besides their pattern or printing, textiles require basic features such as the strong resistance to colour fading agents (e.g. light, usage, washing). This is crucial for the commercial success of the textile. The colours must be uniform and of a solid shade throughout the substrate (Clark, 2011). To assure colourfastness properties, dyes must present high affinity with the fibres, so that the chromophore molecules get fixed, preventing the colours to bleed. These are factors depending on the substrate texture or composition as well as on treatments applied previously or after the dyeing process (Clark, 2011; Malik, Ghromann, & Akhtar, 2014).

Dyes are different from pigments, albeit a common misconception. Besides being soluble or able to become soluble (during application procedures), dyes are retained in the fibres via adsorption, solvation as well as by ionic or covalent chemical bonds (Clarke & Steinle, 1995). Thus, dyes do possess proprieties rendering them susceptible to be manipulated or altered by an infinite number of chemical agents (mordents), a vital medium to help create permanent bonding with fibres. These dyeing substances also differ from each other; they must be applied in different ways, through varied distinctive methods to produce colour in the substrate (Bancroft, 1814; Malik, Ghromann, & Akhtar, 2014). Regarding dyeing application procedures, exhaust dyeing (batch), continuous (padding) and printing are amongst the most common used ones (Clark, 2011).

Dyeing matter possesses peculiar chemical properties that make it very distinct from other materials. This is the backbone of the dyeing process and the reason why colouring substrates is such a complex subject, requiring critical expertise and an extensive amount of knowledge. As already mentioned, each fibre to be coloured requires dyes with specific features, hence thousands of different types of dyes are demanded (Zollinger, 1991; Zollinger, 2003). However, the magnitude of dyes, chemicals and water usage by the textile industry is cause of great emergent ecological concern (Vandevivere, Bianchi, & Verstraete, 1998; Fletcher, 2008; Greenpeace, 2011; Greenpeace International, 2012; Greenpeace, 2012; Malik, Ghromann, & Akhtar, 2014).

Textile effluents are the most pollutant aspect of the textile industry, associated with waste and high levels of contamination. Regarding the usage of water, there are, normally, two types of wasted water during dyeing. One is the dye bath, which contains the remaining dye (exhaustion bath with the extant chromophores that did not get fixed to the substrate) as well as other complex compounds that helped bonding colouring substances and fibres (Clark, 2011). These residues and the amount of dye lost vary, depending on the type of dye used and variations of pattern and colour combinations. The other type of water waste is the wash/rinse water, a procedure to remove any excess dye present in the substrate. In addition to this, water is also needed to clean all the manufacturing components involved in the process (Malik, Ghromann, & Akhtar, 2014). Along with the substantial contamination of water, its waste is a significant problem for the textile sector.

Figure 4 – *Contrapunto BBDO* agency's poster for the World Wildlife Fund (WWF) campaign, raising awareness on global warming and water contamination (Creative Criminals, 2009).

These textile effluents are generally thrown into pure clean waters, representing one of the most critical environmental challenges (Greenpeace, 2012; Malik, Ghromann, & Akhtar, 2014). These contain hazardous substances that are easily able to reach reservoirs and water treatment stations (Greenpeace, 2012), contaminating all ecosystems. Some of the chemicals are harmful, toxic, carcinogenic, mutagenic, corrosive and irritant (Christie, 2007; Greenpeace, 2011; Greenpeace, 2012; Malik, Ghromann, & Akhtar, 2014) and some are known hormone disruptors whilst others can affect the reproductive system (Greenpeace, 2011). Many of these do not break down in the environment, but instead build up in the body of animals and humans, creating mutations (Clarke & Anliker, 1980; Christie, 2007; Greenpeace, 2011; Greenpeace International, 2012; Malik, Ghromann, & Akhtar, 2014) The scarcity of sustainability strategies is, indeed, a colossal problem for the textile sector, especially in the developing countries where the textile dyeing production is massive (e.g. China, India). In flat opposition, alternatives to the issues directly affecting the textile industry ability to sustain itself are barely non-existent.

2.2.1 Mordents

Mordents are chemical compounds used, if required, along with dyes to help fixing them to the fibres. Mordents cannot be applied directly to the fibre but can be used before, during or, in rare occasions, after the dyeing procedure. These mordents are vital to the dyeing industry because most dyes would not bond with the substrate otherwise. These mordents also hold the capacity to alter the colour or hue of a dye; depending on the mordant used in a certain dyeing, different results can be expected in terms of colour (Cleland, Davies, & Llewellyn-Jones, 2007; Fletcher, 2008; Clark, 2011).

Besides mordents, other substances may be used in the textile dyeing procedure as a medium to help the colour fix to the fibres. Some act as dispersers in the dyeing bath, others help the chromophore to penetrate the fibre or aid colourfastness properties. Some of these substances are natural soaps, which make the fibres to wet quicker and the dye to disperse better. These soaps cannot be used in an acid bath or in hard water.

> To make the colour of the dye fast, the dyer either treated the material before dyeing or used mordant dyes that gave fast colours. True mordents were usually a type of natural alum, while materials (such as urine), which were not true mordents but detergents with

an alkaline nature, dissolved acid dyes into proper dyeing solutions. (Humphrey, Oleson, & Sherwood, 1998, p. 357)

Understanding all the means through which the dyeing art evolved since its starting point or how it has developed in the varied parts of the world proves to be a hard task. However, as Bancroft (1814) refers, it is known that ancient populations already used alum as a mordant. In some regions the usage of mordents were considerably advanced, originated by accident or observation long before people were able to write stories or register facts.

Figure 5 - Alum bulk (Wikipedia, 2006).

Varied compounds or mixtures of organic substances were used as mordents. The Greeks and the Romans used urine as a mordent during the Tyrian Purple and Indigo dyeing procedures (Cleland, Davies, & Llewellyn-Jones, 2007). In India, buffalo's milk was used when dyeing with madder (Das, 1992). In Turkey certain oils were used, like rancid olive oil, which main purpose was to keep the dye well distributed throughout the fibre (Liles, 1990).

The most popular mordent was the tannic acid, which is not a specific chemical but rather a mixture of tannin compounds from varied species of plants; it was widely used by different cultures around the world since Ancient times remaining highly popular in the medieval period (Bancroft, 1814). Other mordents, not of organic nature, were heavily used and, unfortunately, are still employed in the current dyeing industry causing concern. These are inorganic compounds such as chrome, copper, iron, tin salts, etc.

> Most natural dyestuff requires a mordent to form a permanent bond with the fibre, and many give a variety of colours with different mordents. Ancient mordents were often naturally occurring chemical earths or metallic salts – i.e. copper, iron or tin. Good effects being given by the simple addition, or use of dye vessels, of naturally oxidized metals – which therefore became objects of trade. Plant acids – from sorrel root or oat galls – or ammonia from urine, can also be used as mordents, and are important in tanning. Mordant may be added to the fibres before or during dyeing – more rarely after dyeing. (Cleland, Davies, & Llewellyn-Jones, 2007, p. 127)

The most successful dyeing procedures were probably the ones applied in protein fibres like wool instead of the ones using cotton or linen as substrates (vegetable fibres). Due to their physical and chemical properties, wool fibre possesses higher affinity with natural dyes, suggesting that in colder regions, where wool was more widely worn, dyeing was explored and appreciated earlier than in regions where cotton and linen were commonly used, i.e. it was significantly superior and far more advanced than in warmer climates. This might also explain why most knowledge and advancements in textile processes and mordenting techniques were discovered, originated or brought from regions such as northern India or western interior China and not from the Mediterranean regions.

> Noteworthy is the intense light fastness and the well-preserved strong colouring of the madder dyes, indicating good saturation of the fibres and a carefully selected mordent process. Various written sources remind us of the high technological standards in Old China. In the oldest Chinese reference work Erh-ya, they speak of a dyeing process in three different steps, which can translate to the pre-treatment of the fibre material through washing and bleaching, its mordent process with appropriate metal salts, and finally the handling of the textile material in one or more dye baths. (Sandberg, 1996, p. 76)

Bancroft (1814) claims that Alexander the Great had access to dyed linen from conquered regions, meaning that the Greeks and the Romans must have acquired some knowledge on the matter when in contact with other regions, most likely techniques from India and Persia, confirming what was suggested above. Either way, the usage of dyed fabric was very restricted, reserved for high classes, the rich, special occasions or in matters of a religious nature (Bancroft, 1814).

2.3 Textile dyes

A dye is a coloured compound extracted only through physical-chemical (dissolution, precipitation, amongst others) or biochemical (fermentation) processes. This coloured substance must be soluble in an aqueous solution (dye bath) in which the material to be dyed is soaked in and, as already mentioned, may require mordents to improve its colourfastness properties (Clark, 2011). Dyes are commonly mistaken as pigments, however whilst both being colorants there are major differences between them. Besides being insoluble, pigments are not affected, physically and chemically, by the medium or substrate in which is merged, unlike dyes (Clarke & Steinle, 1995).

The textile industry is a vast world, with many materials and techniques employed. Involving one of the longest and most complex and difficult chains in manufacturing, it is one of the most pollutant sectors in the world (Fletcher, 2008). It contributes a great deal to poor labour conditions, non-renewable energy and water waste, contamination and environmental impact (Klein, 2000; Bendell & Kleanthous, 2006; Fletcher, 2008; El-Hagar, 2010; Malik, Ghromann, & Akhtar, 2014). Some of its most problematic facets are the finishing processes such as dyeing (Fletcher, 2008; Greenpeace, 2011; Greenpeace, 2012; Greenpeace International, 2012; Malik, Ghromann, & Akhtar, 2014).

2.3.1 Dyeing with synthetic dyes

William Perkin discovered, unintentionally, the first synthetic dye in 1856. In an attempt to work a substance for his developing studies in Malaria treatment, he instead discovered a different colour-producing compound that he would later call and patent *mauveine*. This substance produced an intense purple colour and was able to dye silk with magnificent colourfastness results. Due to its incredible dyeing properties, it was later scaled up. Many other coloured synthetic dyes followed this discovery. This was a revolutionary change as it transformed the world of colour, particularly in the textile field (Garfield, 2000).

Currently, synthetic dyes exist in an unparalleled diversity, to cope with industry needs and consumer demands (Clark, 2011). This class of dyes produce uniform colours and has indeed revolutionised the world of textiles, pushing away natural dyeing compounds only affordable by few.

With their lengthy processes of extraction, production and application as well as extremely high prices (Garfield, 2000), natural dyes were in flat opposition to the novel synthesised dyeing substances; these were cheaper to produce and abundantly available. They also delivered great colourfastness dyeing and plenty of colour shade possibilities. With their introduction to the world, natural dyeing processes and implementation became gradually obsolete. Crucial expertise on ancient dyeing was unsurprisingly lost. Natural textile dyes are, presently, limited in both bio-resources and technical related knowledge (Bechtold, Turcanu, Ganglberger, & Geissler, 2003).

There are, currently, thousands of different types of dyes in the textile industry (Clark, 2011). However, the extent usage of chemicals and water waste by the textile industry is an emergent ecological concern (Malik, Ghromann, & Akhtar, 2014). Although all the advantages offered by synthetic dyeing processes, and after almost a century of its implementation, it is held as unsustainable, i.e. all dyeing techniques and current methods and chemicals involved embody high risks for human and environment integrity (Klein, 2000; Bendell & Kleanthous, 2006; Fletcher, 2008; El-Hagar, 2010; Malik, Ghromann, & Akhtar, 2014). Synthetic dyes production and application has been, increasingly, the target of pollution control boards as the effects of their usage represent serious toxicological issues and a threat to the ecosystems and human health (risks associated with the length of time of exposure to toxicity e.g. oral ingestion, skin and respiratory tract susceptibility) (Clarke & Steinle, 1995; Bendell & Kleanthous, 2006; Nilsson, 2007; Fletcher, 2008; El-Hagar, 2010; Greenpeace, 2011; Greenpeace, 2012; Greenpeace International, 2012; Malik, Ghromann, & Akhtar, 2014).

Textile effluents from finishing processes such as dyeing are generally thrown into pure clean waters before being treated conveniently (Greenpeace, 2012). These hazardous substances are easily able to reach reservoirs and water treatment stations. Some of the chemicals are harmful, toxic, carcinogenic, mutagenic, corrosive and irritant; some are known hormone disruptors whilst others can affect the reproductive system (Greenpeace, 2011); (Greenpeace, 2011). Many of these do not break down in the environment, but instead build up in the body of animals and humans creating mutations (Clarke &

Steinle, 1995; Bendell & Kleanthous, 2006; Nilsson, 2007; Fletcher, 2008; El-Hagar, 2010; Greenpeace, 2011; Greenpeace, 2012; Greenpeace International, 2012; Malik, Ghromann, & Akhtar, 2014). It is estimated that 15% of the worldwide production of dyes is lost to the environment during its manufacture, processing or application (Nilsson, 2007). This number represents approximately two tons of this class of compounds thrown into nature; water is increasingly contaminated.

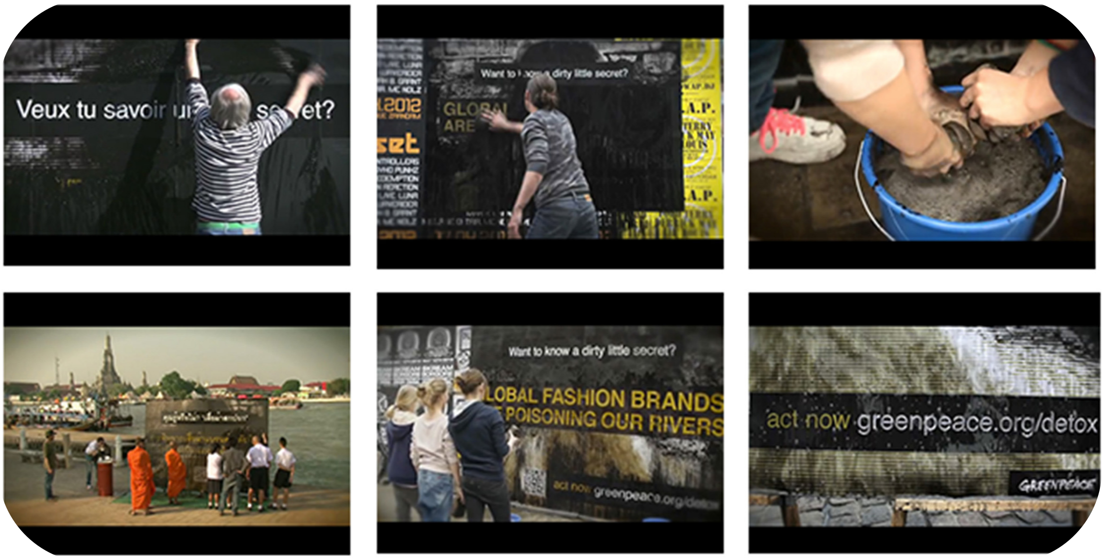


Figure 6 – Greenpeace activists and volunteers plastered cities around the world with posters covered with a special non-toxic ink that was washed away to reveal the fashion industry's dirty little secret. Consumers were then encouraged to take part in washing away the environmentally-friendly, water soluble paint to help raise awareness amongst shoppers and passers-by about the polluting practices of big brands including Ralph Lauren, Calvin Klein and G-Star, with the dripping paint designed to mimic the hazardous chemicals used by the suppliers of these brands (Greenpeace International, 2012).

Toxicological aspects are negative and extended to consumers: health hazards are related to the mode and length of time of exposure, ingestion, skin and breathing susceptibility (Clarke & Anliker, 1980; Clarke & Steinle, 1995; Greenpeace, 2011; Greenpeace, 2012; Greenpeace International, 2012). As these aspects are exposed and debated the legislation turns stricter; pollution control boards are gradually restricting guidelines for the textile industry (Nilsson, 2007).

Table 2 - Advantages and disadvantages of synthetic dyes application

	Advantages	Disadvantages
Synthetic Dyes	Economical	Water waste
	Diversity of shades	Energy waste
	Availability	Pollution
	Great colourfastness	Contamination
	Industrial feasibility	Environmental risks
	Fast processes involved	Health hazards

2.3.2 Dyeing with natural dyes

Designer and consumer expectations towards sustainability in the textile design field triggered some consideration on matters such as climate, environment and health (Bendell & Kleanthous, 2006; Stoddar, 2014). Their awareness on the issues surrounding current production processes is increasing and so their preference for natural materials. This has led to the reintroduction of ancient dyes in the market. Natural dyeing colorants are known for their biodegradable nature and less toxic features (Bechtold, Turcanu, Ganglberger, & Geissler, 2003). They are obtained through biological resources, usually plants or animals, and were used as far back as two thousand years ago (Liles, 1990). Although the higher compatibility with the environment, the usage of natural dyes is tricky not only due to their higher prices but also due to the lack of information and expertise on effective and sustainable techniques of extraction or application (i.e. recipes that deliver great dyeing fastness, deeper knowledge on biological resources) (Bechtold, Turcanu, Ganglberger, & Geissler, 2003).

Most natural substances are known to be unstable in terms of fastness properties and are normally used in addition with other compounds that help the dye fixing to the fibres, generally mordents. Natural dyes are perceived as safer due to their higher level of affinity with the environment, thus, causing less ecological impact. Some ancient dyes can provide for high quality dyeing and bright colour shades, sometimes even without mordents (Liles, 1990). Some natural dyestuff also contains many properties appealing to consumers, especially the vulnerable groups such as elderly, children and babies; they are ecological colouring substances possessing medicinal advantages (Appendix C) such as antimicrobial and antibacterial (Singh, Jain, Panwar, Gupta, & Skhare, 2005; Alihosseini, Kou-San, Jozsef Lango, Hammock, & Sun, 2008; Prusty, Trupti, Nayak, & Das, 2010) and anti-inflammatory properties (Hamburger, 2002). Moreover, related studies indicate that clothes dyed with natural dyes hold a higher level of protection against UVR than the ones dyed with synthetic colorants (Hustvedt & Crews, 2005; Kozlowski, Zaokiv, & Pudel, 2006; Feng, Zhang, Chen, & Zhang, 2007; Grifoni, Bacci, Zipoli, Albanese, & Sabatini, 2011).

However, whilst nature is teeming with colour, not all provided by nature can be used in dyeing, at least for now. Only a small percentage of these natural substances are applied to textiles. Most natural dyes are still unspecified in terms of dyeing properties or methods of extraction, production and application involved. There is great need for research to overcome issues related to the implementation of natural dyes in modern dye houses, particularly regarding optimised and efficient dyeing recipes and their variations (Bechtold, Turcanu, Ganglberger, & Geissler, 2003). Additionally, the amount of dyestuff and colour shades provided is very limited. Dyeing with natural dyes is, consequently, still highly costly. This class of colorants involve rather complex processes - lengthy and arduous extraction methods, high level of difficulty to produce and apply in order to obtain a quality dyeing. To better deal with these aspects, varied studies suggest the usage of innovative technologies, such as ultrasound methods of extraction (Sivakumar, Vijaeeswarri, & Anna, 2011) and application (Vankar, Shanker, Dixit, Mahanta, & Tiwari, 2008). Regarding the water waste, waterless usage procedures to reduce the ecological footprint of the finishing process are being developed and implemented (Dyecoo, 2010).

Although all the natural dyeing substances' benefits and the significant interest of their reintroduction in the market, the challenges around scaling such compounds are complicated. Besides, transferring traditional natural dyeing methods to a modern dye houses require intricate experimentations or redesigning already implemented systems (Leitner, Fitz-Binder, Mahmud-Ali, & Bechtold, 2012).

As mentioned, dyeing is a complex process involving chemical and physical occurrences. By the time of synthetic dyes' introduction to the market dyeing with natural dyes became an obsolete practise and most knowledge on techniques and procedures were lost. In addition, there is an extensive amount of data that has yet to be recorded; there is, still, very little info on biological resources possessing dyeing potential material. Recent studies, and governments, prioritise the search for new biological resources, identifying new species of fauna and flora, for the purpose. The significance of such data lies on the hypothesis of certain coloured compounds to be isolated and tested in textile fibres and better evaluate their dyeing efficiency. Again, further research on the subject is imperative and will be key to overcoming sustainability issues in the textile design sector. These are a few reasons why natural dyes usage is such a challenging subject; their practicability at a massive industrial scale is, so far, not easily attained. These demands call for, besides deeper scientific research, finding alternatives in sustainable dyeing or embracing radical innovative ways of creating and manufacturing materials as discussed later on in this dissertation.

Table 3 – Advantages and disadvantages of natural dyes application

	Advantages	Disadvantages
	Degradable nature	Expensive
	Medicinal properties	Difficult methods of extraction
Natural Dyes	Higher UVR protection	Limited production
	Ecological	Restricted resource knowledge
	Biodiversity protection	Scarcity of recipes
	Colourfastness	Scale-up difficulty

2.3.3 Ancient textile dyes and their biological resources

Both dyes and pigments are powerful colorants. The basic difference between them is that dyes are soluble and pigments tend to leave residues, as they are insoluble in water and most of the solvents. Natural dyes are colouring substances extracted from animal or vegetal raw materials, through physic-chemical (dissolution, precipitation, etc.) or biochemical (fermentation) processes (Clark, 2011).

Ancient dyes were used until the end of the nineteenth century with some dating back to 4000 BC. Although most of the natural compounds are branded for poor colourfastness there were dyes used in ancient times that became, indeed, extremely important in the dyeing industry; their possession and related expertise were often the reason for riches and dispute (Greenfield, 2005). The colour shades provided in ancient times were, obviously, limited to the biological resources at hand and the expertise on mordents and dyeing techniques.

Next, natural dyes are examined in order to assess the procedures and techniques related as well as their properties. Understanding their provenience, evolution, methods of extraction, length of procedures, etc., is critical for the comprehension of what is intended to discuss, prove and propose in this dissertation. This analysis helps, simultaneously, to highlight the array of colours that may be provided by this class of dyes.

Figure 7 - These colours are obtained from madder roots, indigo and turmeric. These natural compounds are applied to dye the famous Persian rugs. (Asran Decor, 2012).

2.3.3.1 Natural dyes producing red shades

Until the discovery of synthetic dyes, reddish shades were provided by natural dyes such as madder, brazilwood, annatto, kermes, cochineal, etc. These are amongst the most known ancient dyes, extracted from plants, trees, insects or molluscs.

Madder can be extracted from varied species of *Rubia* plant; the Asian specie is *Rubia cordifolia* and the European one is called *Rubia tinctorum* (fig. 8). *Rubia*'s properties are well documented.

It is rather difficult to accurately confirm the date, or the place, this plant started being harvested or when it began to be used as a dyeing material. However, according to chemical analysis, madder was a popular dye in Asia and in the Middle East; it was identified in archaeological excavations in Mohenro-daro, actual India and Pakistan boarder, dating from 3000 BC (Bhardwaj & Jain, 1982).

Figure 8 - *Rubia tinctorum* plant (Wikimedia Commons, 2010) and its roots where the dyeing substance is gathered (Ever Green Knits, 2014).

Chemical analyses also reveal that Chinese held better acquaintance within the dyeing processes, as confirmed through textile material dated from 3400 BC collected from archaeological sites in Xinjiang. These studies reveal Chinese possessed strong knowledge on mordents, which resulted in wonderful fabrics with technically well-applied uniform colours (Zhang, Good, & Larsen, 2008).

Studies have shown that, in the final first millennium BC, *Rubia tinctorum* was exhaustively harvested in Persia (Iran), Anatolia (Turkey) and in the Mediterranean (Zohary & Hopf, 2000). When analysing material collected from Tutankhamon's tomb, textiles were found and are believed to have been dyed with madder however, as suggested by the poor dyeing values displayed in fibres at the time of chemical analysis, it was concluded that Egyptians were not fully acquainted with mordent techniques. The many studies by Pisame study also indicated that the purple displayed in the cloths could not be the famous Tyrian purple but rather a mixture of *Rubia tinctorum* (madder-red) with *Isatis tinctorium* (indigo-blue) (Sandberg, 1996).

The colouring compound extracted from *Rubia tinctorum* was, until the end of nineteenth century, one of the most important natural dyes in Europe and in Southeast Asia. It is concentrated in the roots of the plant (fig. 9). It can be applied to linen, cotton, wool and leather; madder is a dye that needs a pre-mordent, generally alum and iron compounds. In many procedures, calcium salt is recommended for a faster colouration and greater brightness (Serrano, Lopes, & Seruya, 2007). Adding aluminium salt allows for shades of red, tin salts for shades of orange, aluminium and ferric salts for shades of brown, calcium salts for bluish red, ferric salts for dark purple (Zohary & Hopf, 2000).

Figure 9 - Varied tones of red using madder as a natural dye (Sea Green and Sapphire, 2012).

Chemically, madder is a complex mixture of anthraquinones (Sandberg, 1996), the majority being the alizarin (fig.10), purpurin and pseudopurpurin (Edwards & Chalmers, 2005).

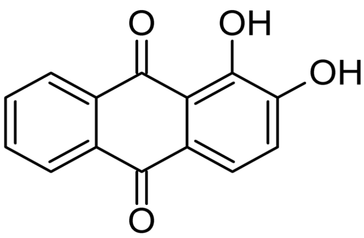


Figure 10 - Chemical structure of alizarin (Wikimedia Commons, 2007)

Brazilwood is obtained from the varied species of *Caesalpinia*. The most known species are the *Caesalpinia sappan* (Asiatic specie), from India, Sri Lanka and Malaysia and *Caesalpinia echinata*, from the Atlantic coast (fig. 11). The dyeing compound extracted from this tree may be applied to wool, silk and cotton (Serrano, Lopes, & Seruya, 2007).

Figure 11 - *Caesalpinia echinata* tree (Wikimedia Commons, 2010). The dye is extracted from the bark of the tree and originates varied tones of red, according to the types of mordent used (Brush Creek Wool Works, 2015).

Brazilwood was a very important dye in the Medieval Age; Ceylon was at the time the biggest production centre. Sent to Alexandria from Ceylon, brazilwood would then head to Europe. It is possible that brazilwood traded in Europe corresponded to varied species of *Caesalpinia*, since the dyeing substance – brazilin (fig. 12) - can be found in many of these trees (Thomson, 1838). Information on trade is scarce, however, some authors suggest that it was initially coming from Asia in limited quantity and later in a much larger scale through the Portuguese on their arrival to Brazil (Armstrong, 1992). Brazil's (the country) etymology comes from *brasa* meaning fire, reddish shade (Bancroft, 1814).

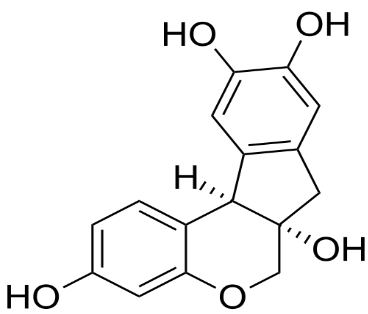


Figure 12 - Chemical structure of brazilin (Wikipedia, 2012)

The annatto dye is extracted from the *Bixa orellana* specie (fig. 13). *Bixa orellana* is a shrub originally from Guiana, South America, which can reach up as high as 10 metres; Brazil is its main producer and exporter. It also grows in Central America and Philippines (introduced through the Spaniards) and Africa where it used to be largely harvested (Jansen & Cardon, 2005). This plant produces a natural dye called Annatto.

Figure 13 - *Bixa Orellana* species. This tree produces annatto dye, which is extracted from its seeds (Wikispecies, 2007).

Some chemical analysis, performed to textiles found at the archaeological site in the Azapa region, place this dye somewhere between 300 AD and 1500 AD (Boytner, Cassman, & Schleicher, 2002). The colouring principal is obtained through the fruit seeds that must be picked when ripened and should be air-dried (not under the sun) (São José & Rebouças, 1991). After this they are crushed and immersed in water; through evaporation of this aqueous solution an intense orange-reddish mass is obtained and can be applied to cotton, wool and silk fibres (Jansen & Cardon, 2005). This dye provides shades ranging from red to ochre colour (Bancroft, 1814). Colour occurs due to the presence of several apo-carotenoids, bixin (fig. 14) being the majority (bixa orellana, 2009).

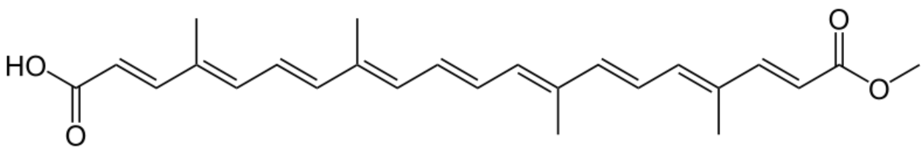


Figure 14 - Chemical structure of bixin (Wikimedia Commons, 2007).

The next figure, *Baphia nítida* (aka Camwood plant) is a tree native to Gabon and

Senegal and has been harvested in other countries in Africa such as Liberia and Sierra Leone. It is source of a red shade producing dye, known for centuries.


Figure 15 - *Baphia nitida*, also known as African sandalwood or camwood (Wikimedia Commons, 2014).

It was first large-scale exported to Europe in the 17th century and then to America on the following one. Dyers at the time considered this plant to be extremely rich in dyeing material, generally applied to wool, silk and cotton fibres. Coloured substance (fig. 16) can be found in the interior of the tree and can be extracted through basic solutions and alcohol; leaves are rich in tannins. Dyeing material was not only applied to achieve red shades but it could also be used to obtain a range of brown and bronze tones if combined with other trees' coloured substances (e.g. *Haematoxylum campechianum*) (Jansen & Cardon, 2005).

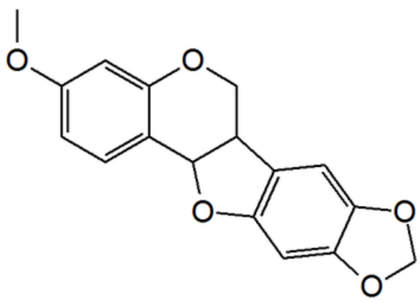


Figure 16 - Pterocarpin is the chemical substance found in the *Bahia nitida* tree that enables the dyeing (Wikipedia, 2015).

Few substances obtained through animals were used as textile dyes. However, due to their rare nature or rather complex extraction methods, these dyes were very valuable. The most important ones were the dyes obtain by insects or sea snails.

Kermes is a bright red dye produced by an insect. The most common species providing this dye are the *Kermes illici* and the *Kermococcus ilex* or *vermilius* (fig. 17) that live in certain species of *Quercus* trees and other plants. They inhabit the Mediterranean and some parts of the Middle East (Amar, Gottlieb, Varshavsky, & Iluz, 2005). Other species of this family can also be found in varied regions: *Kermes biblicus* and *Kermes spatulatus* in North Israel, Kimiz in Turkey and Armenia, *Margarodes polonicus* and *Porphyrophorus polonicus* in Poland, Germany, Lithuania, Ukraine; *Coccus fragariae* in Siberia, *Coccus uva ursi* in Russia (Sandberg, 1996).

Figure 17 - These red pockets are actually the reaction of the worm *kermococcus* specie's bite on the leaves, used as cocoons. After reduced to powder it originates the crimson dye that produces scarlet-red tones (Nascimento, 2014).

There is literature indicating that the Phoenicians were the first ones recognising this substance as a dyeing compound and it was used as such by the Babylonians. The Bible book, *Old Testament*, mentions a bright red colour that according to different historians was obtained through this insect (Amar, Gottlieb, Varshavsky, & Iluz, 2005; Bancroft, 1814):

> Being unacquainted with the oriental languages, I can only adduce to this point the opinions of others, better qualified than myself in that respect. One of these is Professor Tychsen, (quoted by professor Beckman, vol. II. p. 185 of the English translation of his History of Inventions,) who says, that among the Hebrews, the kermes dye was mentioned, under the names of "tola schani, or simply tola, by their oldest writer, Moses", that "tola is properly the worm" and that "the additional word schani, signifies either double dyed, or, according to another derivation, bright, deep, red dye;" that for the shell "purple, the orientals have a particular name, argaman or argevan, which is accurately distinguished from tola". (Bancroft, 2008, p. 292-293)

According to Sandberg (1997, p. 57), the Sicilian author, Flavius Vopiscus, from 300 AD, describes in one of his writings a situation involving a piece of wool cloth offered to Marcus Aurelius, the roman emperor, by the Persian ruler:

> Woollen cloth which had a more beautiful and brighter purple red color than any previously seen in the Roman Empire! Compared to these textiles, the purple clothing worn by the emperor and the ladies of the court appeared dull and faded. Experienced dyers were sent from Rome to India to seek what they believed to be the colour purple, as well as knowledge of the dyeing method. However, they returned without having found the article, and could only leave a vague report that basically stated that the Persian "purple" was produced from some sort of plant. (Sandberg, 1996, p. 57)

Although aware of the existence of this specific dye, Romans were not familiarised with mordents, dyeing techniques long ago being applied by the Indians and the Persians. Apparently, the use of Kermes as a natural textile dye was used since our chronology, as suggested by many authors; the Chinese are thought to have used this dye since the first centuries AD as well as the Egyptians, who used it in a larger scale during the Muslim Empire, in the 7th century, as revealed through the results from the chemical spectroscopic analysis ran on the archaeological Egyptian pieces, mainly to textiles dated between the 4th and the 12th centuries (Bechtold & Mussak, 2009, p.32). Bancroft (1814) mentions the existence of detailed descriptions about the harvesting of this insect in the book *Beschreibung von Allerley Insekten*, edited in Berlin in the 18th century. This explains the picking of Kermes insect during the 12th century in Germany.

Figure 18 - The kermes dyed Mantle of Roger II King of Sicily. It is dated from 12th century (Causes of color, 2015).

This dye was commercialised in the form of small brown reddish balls (approximately the size of a pea). These are the eggs of insects hat are laid on the tree branches. After being dried and grinded an intense bright red soluble dye would be obtained. This was such an important dye that the pope Paul II decreed, in 1467, cardinal's clothes to be dyed with it, rather than with the expensive Tyrian Purple, as it was until then. The colouring principle is kermesic acid as shown in figure 19 (Sandberg, 1996).

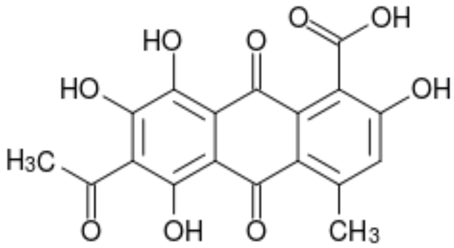


Figure 19 - Kermesic acid, responsible for the kermes natural dye (Wikimedia commons, 2013).

A similar insect providing bright red is the specie *Nopalea coccinilifera* or the *Dactylopius coccus*, both native to Mexico. Cochineal can be found in the cactus species *Opuntia ficus-indica* (fig. 20). According to Bancroft (2008), it was extensively used by the Aztecs and the Incas and later on by the Spaniards, who recognised its greater dyeing potential, higher in quality than Kermes.

Figure 20 - *Dactilopius coccus* species on a *Opuntia ficus-indica* cactus plant (Wikimedia commons, 2011).

Figure 21 - Carmin or cochineal dye can deliver varied shades of red (Knotted Quipus, 2012).

> A legendary red dye that was once one of the world's most precious commodities. Treasured by the ancients Mexicans, cochineal was sold in the great Aztec marketplaces, where it attracted the attention of the Spanish conquistadors in 1519. Shipped to Europe, the dye created a sensation; producing the brightest, strongest red the world had ever seen. Soon Spain's cochineal monopoly was worth a fortune. (Greenfield, 2006)

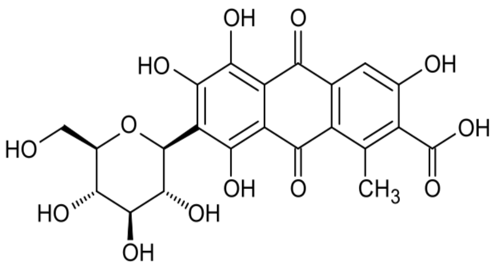


Figure 22 - Carminic acid's chemical structure (Wkimedia commons, 2010).

2.3.3.2 Natural dyes producing yellow shades

Native to Europe, West Asia and North Africa (Goffer, 1980), *Reseda luteola* depict in figure 23, produces a dye called weld, able to provide an intense yellow colour. Cromophores contained in this plant were discovered in Viking textiles (silk fabrics believed to be imported from Asia). Through varied spectroscopic analysis, the dye was positioned as far 2000 years ago, at least in Europe and Middle East (Zhang, Good, & Larsen, 2008).

Figure 23 - *Reseda luteola* plant (Wikipedia, 2008) and the colour shades that can be obtain through weld dye (Brush Creek Wool Works, 2015).

The colouring matter is spread all over the plant and it is more concentrated in the seeds and top branches. The plants were normally acquired when already dried and were, then, boiled in water. This water could be mixed with urine or potassium hydroxide in order to ease the extraction process. This dye provided for a very pure and stable yellow and allowed for a range of various yellow and green shades depending on the mordent applied (i.e., yellow shades – aluminium salts, orange shades – tin salts, olive green – ferric salts, brown shades – chromium (Serrano, Lopes, & Seruya, 2007). The colouring principal is luteolin:

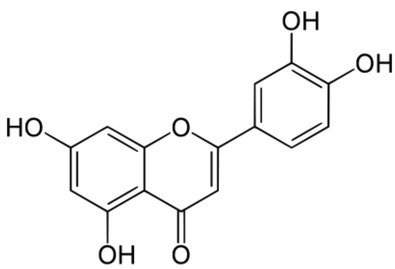


Figure 24 - Luteolin's chemical structure (Wikipedia, 2008).

Mahonia napaulensis DC is a plant that also produces a strong yellow dye. This plant grows in the Indian region of Arunachal Pradesh, more precisely in the Ziro valley in Subansiri. It is used as a textile dye's source since ancient times until present-day by the Apatani tribe. Recent studies suggest it has strong dyeing potential and might be scientifically developed in order to substitute a certain synthetic dye.

Figure 25 - *Mahonia napaulensis DC* plant (Wikipedia, 2012).

Mahonia napaulensis DC possesses a substance called berberine, which is extracted from the stems and wood and has a yellow greenish colour. When combined with metallic mordents, and applied to cotton, it originates shades of beige to khaki. Bright shades of orange can be achieved when applied to protein fibres (Vankar, Shanker, Dixit, Mahanta, & Tiwari, 2008).

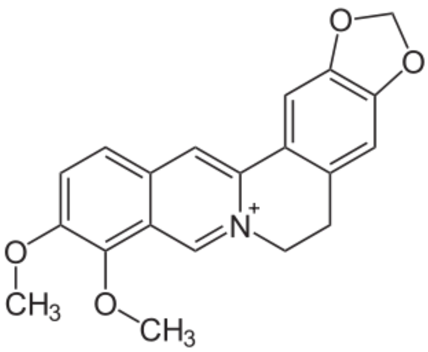


Figure 26 - Chemical structure of berberine (Wikipedia, 2008).

Saffron is a red brownish or golden yellow coloured substance extracted from *Croscus sativus* (fig. 27), a plant that is highly adaptable to a wide range of climates, from temperate to sub-tropical. It is native to Greece, Turkey and Iran. Later on it was introduced throughout the Middle East and Europe, where it is still heavily harvested (Jansen & Cardon, 2005; Serrano, Lopes, & Seruya, 2007).

Figure 27 - *Crocus sativus* plant (Wikipedia, 2005) and dried styles and stigmas – saffron threads (Wikipedia, 2015).

It was harvested in Persia long before the Christian era and was introduced to China through Mongol nomads (Bender, 1947; Serrano, Lopes, & Seruya, 2007). Its colouring substance can be found on the flower stigmas. To ease up solubility these stigmas are reduced to a powder after dried.

Figure 28 - In India, Tibet, and China, saffron has been used to produce the yellow-red colour of robes for Hindu and Buddhist monks (Dharmananda, 2005).

This dye is one of the rare direct dyes occurring in nature, therefore no need for mordent application to form the dye-fibre fix (Serrano, Lopes, & Seruya, 2007). The yellow colour is due to the presence of crocetin substance and its glycoside – crocin as shown in the following figure.

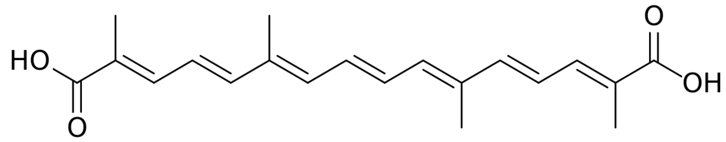


Figure 29 - Crocetin chemical structure. The chemical structure of crocetin forms the central core of crocin, the compound responsible for the colour of saffron (Wikipedia, 2014).

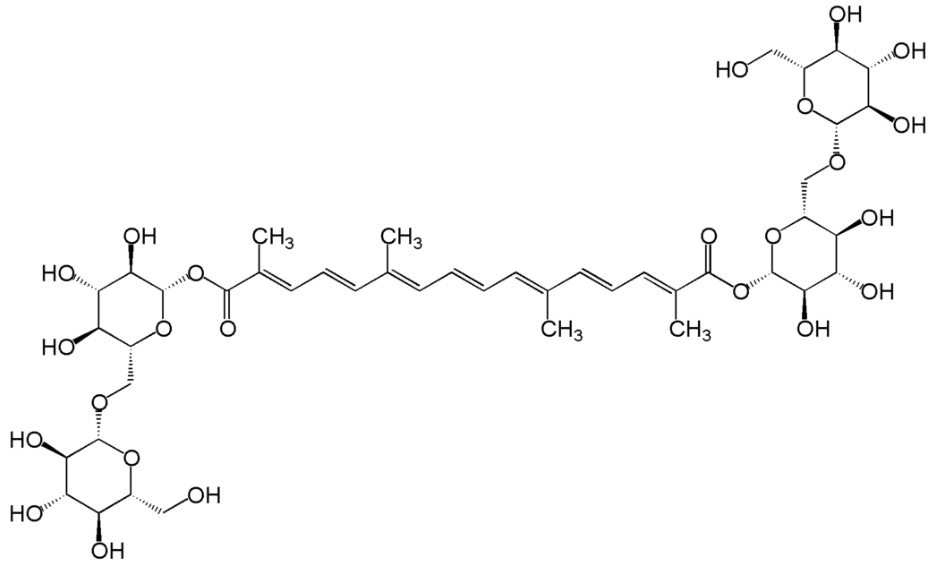


Figure 30 - Crocin chemical structure (Wikipedia, 2014).

Similarly, *Carthamus tinctorius* (fig. 31), also known by the names of Safflower or Saphron-bastard, is a plant that produces yellowish tones. It is well adapted to temperate and subtropical climates and it is native to China, India, Persia, Egypt and South Europe.

Characterised as an herb with a whitish stem and thorny alternating leaves, these plants produce a dyeing substance that is obtained through the washing of their orange flowers: petals are picked fresh and carefully air-dried, to remove the yellow dyeing substance they are kneaded along with water. The remaining mass is pressed into cake shapes and put to dry. In the traditional Indian method, the extraction is made through repeated washings in acidic water during several days.

Figure 31 - *Carthamus tinctorius* (Wikipedia, 2006) and its dried stigmas, saffron-bastard (Wikipedia, 2009).

The colouring matter is formed by carthamin and carthamon (Serrano, Lopes, & Seruya, 2007). In the traditional method, the last colouring matter is deliberately removed from the flowers through washing, to allow for a possible red dye substance. The red variety contains red carthamin; the yellow contains neocarthamin and less carthamin and the orange variety contains carthamon as well as carthamin (Bancroft, 1814; Serrano, Lopes, & Seruya, 2007):

> It is the flower only of this plant which is employed in dyeing, and which affords two sorts of colouring matter, one soluble in water, and producing a yellow of but little beauty, when dyed adjectively, on an aluminous basis; the other is resinous, and best dissolved by the fixed alkalis: it is this last which alone renders safflower valuable in dyeing, as it affords a red colour, exceeding in delicacy and beauty. (Bancroft, 1814)

Figure 32 - Safflower is a unique dye source as their delicate petals contain two dyeing substances - yellow and pink. Both colours can be extracted from a single batch of petals by first removing the yellow in water, then the pink in an alkaline solution (Corbet, 2010).

After the dyeing substance is extracted from the flower petals, the remaining residues are treated with a basic solution to extract carthamin (fig. 33). The petals are filtered and then neutralised with a weak acidic solution. This dyeing matter is able to produce shades of red and pink in linen and cotton fibres but show poor results to light fastness. In silk and wool fibres, and depending on the mordents, shades of yellow (aluminium) and brown (copper) can be obtained.

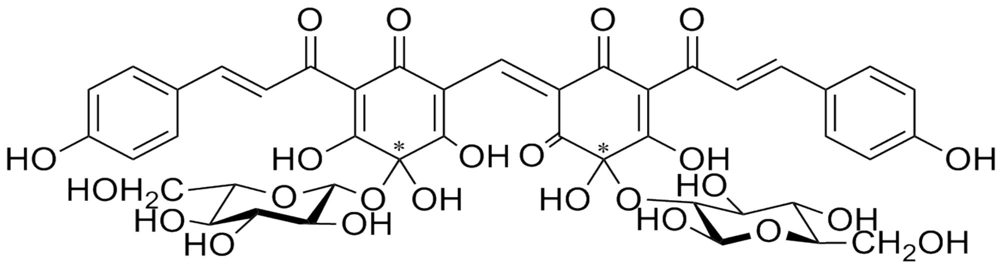


Figure 33 - Carthamin's chemical structure (Wikipedia, 2015).

Chlorophora tinctoria, also named *Maclura tinctoria* (Bechtold & Mussak, 2009, p.25), produces a dye commonly called Fustic (Thomson, 1838). *Chlorophora tinctoria* is a tree that can reach up to 40 metres height and 1 metre wide. It can be found in all Central America as well as some countries in the south as Venezuela, Brazil, Peru or South Europe (Smithsonian Tropical Research Institute, 2004). This yellow natural dye started to be commercialised in Europe after its introduction through the Spaniards (Bechtold & Mussak, 2009).

Figure 34 - *Chlorophora tinctoria*, also named *Maclura tinctoria* is a tree from which old fustic dye is obtained. (Smithsonian Tropical Research Institute, 2004).

The colouring matter is a flavonoid - morin -, depict in figure 35. This yellow crystalline substance is extracted from the wood through boiling water, originating an orange reddish solution that becomes yellow through dilution. After the purification process this dye is ready to be applied producing a bright yellow tone. It can be used in wool and cotton substrates (Thomson, 1838). Shades also vary depending on the mordents applied - orange (alum), brown-reddish (chromium or tin), and yellow (no need for mordents). Colours show good resistance to washings but poor luminosity (Serrano, Lopes, & Seruya, 2007).

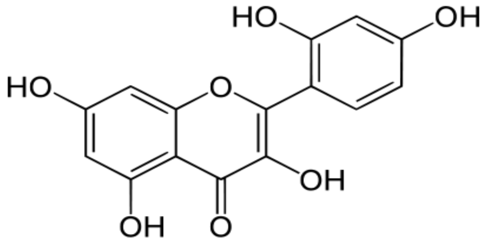


Figure 35 - Chemical structure of morin, responsible for the yellow colouring of the yellow from old fustic dye (Wikipedia, 2008).

2.3.3.3 Natural dyes producing blue and purple shades

Indigo is a bluish colouring substance obtained from different species of *Isatis tinctoria* and *Indigoferae*, depict in figure 36. The name indigo comes from the latin *indicum* which means "from India" and it is the only known blue dye since early times, considered by many historians as the most ancient dye in history, used for, at least, 4000 years (Bancroft, 1814).

The substance obtained from the species *Indigoferae* is stronger in dyeing matter than the European specie *Isatis* (woad), which provides a lower quality, and less concentrated, dye (Serrano, Lopes, & Seruya, 2007). Indigo dye was found in several ancient Egyptian blue textiles from the 18th Tell el Amarna dynasty, around 1370 BC (Zohary & Hopf, 2000).

Figure 36 - *Isatis tinctoria* (Wikipedia, 2005) (left) and the species *Indigofera tinctoria* (right) (Wikipedia, 2004).

Indigo production reached its peak during the 19th century. During the British colonisation period in India, great plantations of *Indigoferae* were harvested. The Indigo production and commercialisation was one of the greatest sources of income of the region (Zohary & Hopf, 2000). This massive indigo production collapsed after the introduction of a cheaper way to chemically synthesise this dye, in the 19th century. Unlike other substances, indigo does not occur in the plant itself but is rather created during the extraction process, which has not seen many changes since ancient times (Bechtold & Mussak, 2009).

Figure 37 - Shades of indigo blue (Thanking the Spoon, 2015).

Indigo is non-soluble in water so it must go through a chemical process transformation. In Europe, this transformation consisted in the use of urine to dissolve the dye, a method that was already used by the Romans and the Greeks. Urine reduces indigo, which is not soluble in water, into a soluble substance (known as white indigo or leuco-indigo) that would then be applied to silk or wool fabrics. After oxidation white indigo becomes blue indigo. After the 19th century urine was substituted by synthetic urea.

One of the methods is explained by Serrano, Lopes & Seruya (2007) as follows: after picking, leaves must be immersed in water during 9 to 14 hours and then grinded and shaped into round cakes left to rest; the fermentation allows for the disintegration of the dyeing matter present in the leaves, in the form of a glycoside, which is, in turn, hydrolysed to glucose and reduced to a leuco-solution, soluble in water. The resulting solution is then collected and left to dry in order for the oxidation to occur. After precipitation, top layer is decanted and the resulting mass is dried and ready to be applied as a dye.

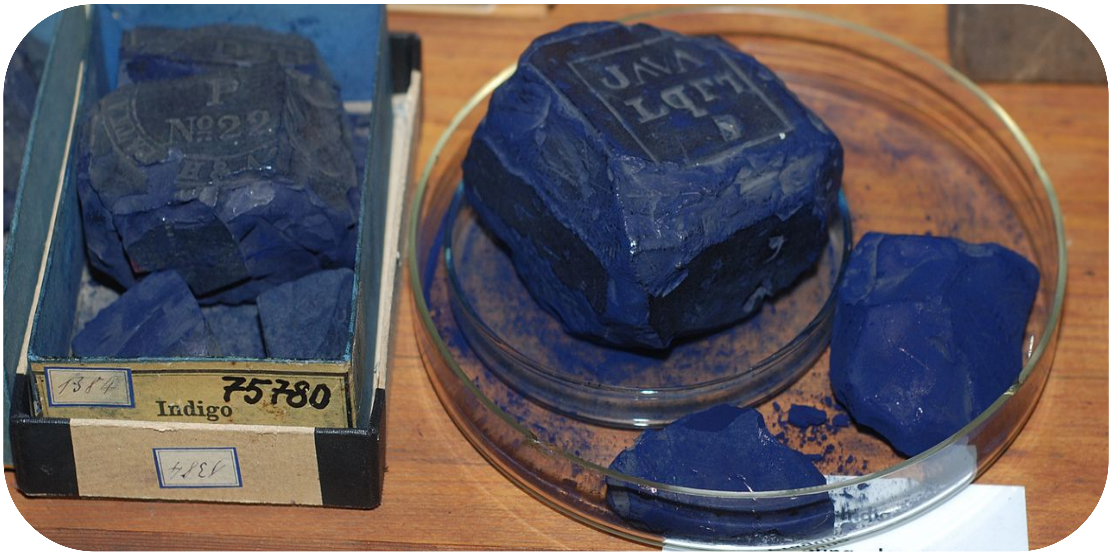


Figure 38 - Indigo, historical dye collection the Technical University of Dresden, Germany (Wikipedia, 2012).

In the indigo dyeing application process mordents like alum can be used in order to achieve different shades of blue; to obtain shades of grey the mordents copper or chromium may be added (Serrano, Lopes, & Seruya, 2007).

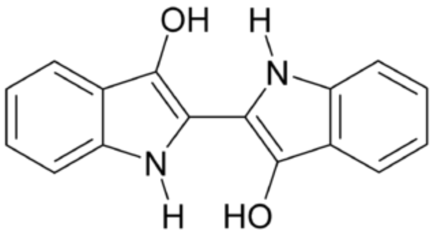


Figure 39 - Chemical structure of Indigo white (leuco-indigo) (Wikipedia, 2007).

Dyes producing blue or purple shades of colour can also be obtained via specific marine molluscs. From all the applications that molluscs have had, being a source of the most important and expensive dye in history – Tyrian Purple - is certainly one of the most remarkable facts.

When analysing this biological resource (producing such potent direct dye), it can only be speculated that sea creatures hide plenty of wonderful tinting substances, waiting to be tested and verified, holding, perhaps, powerful textile dyeing properties, similarly to Tyrian Purple (truth is most marine gastropod molluscs secrete either inks or fluids containing chromophores). The next figure portrays a sea snail from the *Aplysia* species, squirting a cloud of ink as a defensive mechanism (much like the octopus and the squid). The beautiful display of colour, released when distressed, reveals violet shade chomophores that could easily contain dyeing potential.

Figure 40 – *Aplysiomorpha* from *Aplysia* species releasing ink under the sea when disturbed (Anderson, 2003).

Alas, concerning its ink properties and the ability of, hypothetically, producing a strong textile dye, information is non-existent in regards to the subject (as they have never been studied to that purpose). Again, this example offers an idea on how much unawareness subsists concerning the subject of biodiversity, on what it may provide or its infinite properties. It is most important for the present research that knowledge on biological resources is grasped as we can, currently, synthesise natural matter in cheaper ways and in greater quantity, through sophisticated technologies such as synthetic biology as explained later on.

Regarding Tyrian purple (aka Royal or Imperial purple), the species producing the most valuable dye of Ancient Times, are generally the *Murex* family, some of which are shown in figure 41, below. They can be found in different parts of the world, i.e. in Tyre and Sidon the species *Murex brandaris* and *Murex trunculus* (fig. 41); in the Pacific coast of Central America the *Purpura patula*; Indian Ocean the *Murex pecten* or *Purpura persicaria*; *Nucella lapillus* in British Isles and Scandinavia (Sandberg, 1996).

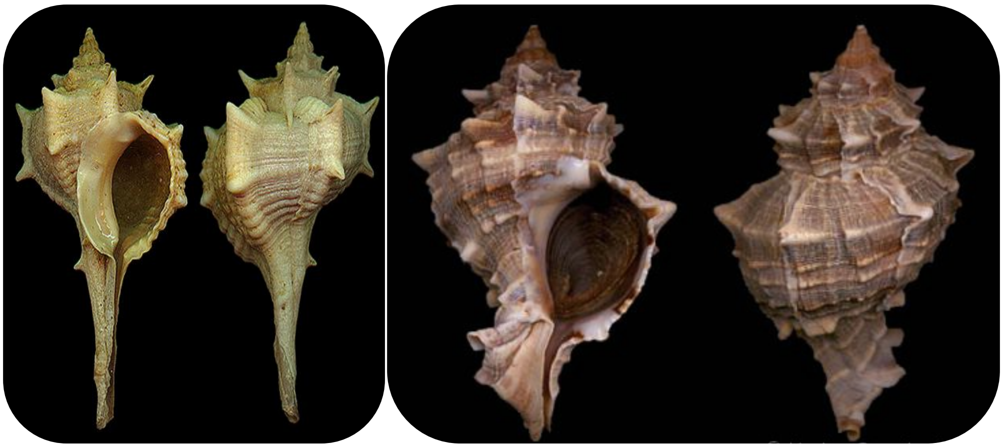


Figure 41 - *Murex* sea snails – biological resource for the Tyrian Purple dye; *Murex brandaris* on the left and *Murex trunculus* on the right (Gastropods, 2015).

These *Murex* sea snails produce a dye known as Tyrian Purple, symbol of power, distinction and abundance; the more violet was worn, the higher the importance of the person exhibiting it; its extremely high price is related to the difficulty of extraction and with the quantity provided (to obtain one gram of dye powder, thousands of sea snails are required) (Sandberg, 1996).

> The limited access to purple molluscs, the minimal quantity of the dye-producing secretion, and the degree of difficulty involved in the dyeing process made purple-colored products enormously expensive to produce. Naturally they became the most expensive of antiquity's goods, reserved for kings, emperors, and the upper classes of society. (Sandberg, 1996)

Some authors believe their application can be traced back to 5000 BC (Benkendorff, et al., 2015). There is evidence suggesting that the Minoans, in Crete, were already acquainted with it as a textile dye, around 1600 BC (Bancroft, 1814) (Jackson, 1917), yet, as the name implies, it became famous through the trades in the Mediterranean by the Phoenicians, along with their extensive dye production industry, in approximately 1500 BC (Bancroft, 1814). Tyrian purple produces a range of shades that can vary from blue to violet and deep purple.

Figure 42 - Tyrian purple colour (Belle, 2013).

The coloured compound is present in a mucous secretion produced in the hypobranchial gland. This secretion is colourless whilst fresh but changes when exposed to the sun, turning to yellow, then green and finally purple – its characteristic colour (Sandberg, 1996). Natural dyes extraction and application methods are commonly difficult and in the case of Tyrian purple dye this is no exception. Pliny, the Elder (1963) and Sandberg (1996) both describe the typical ancient application process as extensive: after spring (best season to pick the shells) thousands of sea snails were gathered and grinded; after all the crushing the next step would be salting this mixture and leaving it to rest, to steep for three days; afterwards, the mixture would be boiled over a ten day period, after which it would finally be ready to decanter. Similar to indigo dye application, the final result is a clear solution where the fibres can be soaked and hung in the sun so the colour starts to show (Pliny, 1963; Sandberg, 1996).

Tyrian purple is a direct dye, which means that can be applied without mordent. In figure 43, a direct application of the dye in the fibre can be appreciated; in this case, no depletion of the mollusc occurs as it does in the method explained above.

Figure 43 - Tyrian purple being milked directly from the *Murex* specie onto the fibre (Mindling, 2013).

Chemically, its colouring principle is the 6.6'-dibromoindigo and it presents, amongst many others, antimicrobial and antibacterial properties (Benkendorff, et al., 2015).

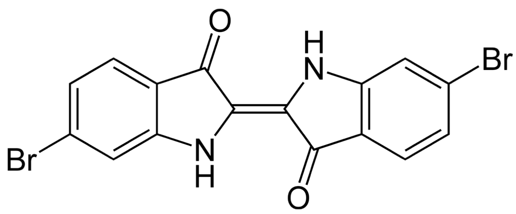


Figure 44 – Chemical structure of 6.6' dibromoindigo, the main component of Tyrian purple (Wikipedia, 2011).

Other living organisms are able to produce colouring matter. This is true for varied microorganisms (e.g. bacteria, fungi, microalgae), able to produce by-products that may be tested as a potential dyeing material and to better evaluate their performance as well as their fastness properties.

Figure 45 – Similar to indigo, the final result is a clear solution where the fibres can be soaked and hung in the sun so the colour starts to show (Mindling, 2013).

As stated in 2010, in *Corantes têxteis naturais: a Biotecnologia da Antiguidade ao século XXI (Natural textile dyes: Biotechnology from Ancient times until the 21st century)*, a lot more research is needed in order to verify the possibilities of such biological resources. As mentioned in the same study, there is the reference to the following species as potential textile dyeing resources: *Streptomyces coelicolor* (blue); *Chomobacterium violaceum* and *Janthinobacterium lividum* (violet); *Monascus sp, Phaffia rhodozyma, Micrococcus rouseus, Brevibacterium linens, Bradyhizobium sp* and *Xanthomonas campestris* (yellow and red) (Santos, 2010). These dyes are produced by a phenomenon occurring naturally in nature; however, by manipulating at times their environment (e.g. diet, location) further properties can be altered or even enhanced. Additionally, as extensively examined later on, microorganisms can be, currently, modified and engineered to produce other dyeing substances via modern biotechnologies. This is a promising method as asserted by Santos (2010, pag.109) as "microorganisms possess a high level of growth and reproduction".

2.3.4 Natural Dyes' colour shades and location

Table 4 – Biological resources, chemical substances, colour shades and geographical location on some natural textile dyes. (Santos, 2010) (Appendix G and H)

Source	Substance	Shades	Location
Rubia tinctorum	Alizarin / Purpurin (Anthraquinones)	Bright Red Brown	Europe, Asia, Middle East
Caesalpina echinata	Brasilin	Orange Brown	America, Asia
Bixa orellana	Bixin / Isobixin	Red / Orange Dark Yellow	America, Asia, Africa
Reseda luteola	Luteolin (flavonoid)	Bright Yellow / Orange Green / Brown	Asia, Europe, Northern Africa
Crocus sativa	Crocetin / Crocin	Yellow / Orange	East, Europe, Asia
Isatis tinctorum Indigoferae	Indigo	Blue / Grey	China, Asia, America, Europe, Africa Sub-Saharan
Anogeissus leiocarpa	Gallic and Ellagic acid (Flavonoids)	Yellow / Ochre Red / Black	Africa
Haemotoxylon campechianum	Hematoxylin	Purple / Violet Blue / Black	America, Europe
Kermococcus vermilis	Kerminic acid	Red	Europe, East, Asia
Dactylopius coccus	Carminic acid	Red / Pink / Violet	America, Mediterranean
Murex	6.6' dibromo-Indigo	Red / Pink / Violet Purple / Blue	Europe, East, America
Chomobacterium violaceum	Violacein	Violet / Purple	Glacier - China
Streptomyces coelicolor	---	Blue	---
Monascus sp Micrococcus roseus	Carotenoid	Yellow Red	---

3. Biotechnology

3.1 Classic and Modern biotechnology

> Biotechnology impinges on everyone's lives. It is one of the major technologies of the twenty-first century. Its huge, wide-ranging, multidisciplinary activities include recombinant DNA techniques, cloning and genetics, and the application of good as prosaic as bread, beer, cheese and antibiotics. It continues to revolutionize treatments of many diseases and is used to provide clean technologies and to deal with environmental problems. (Ratledge & Kristiansen, 2001)

As a consequence to scientific breakthroughs occurred last century, we currently possess, given the discovery of the genetic code transmission's responsible molecule (DNA), techniques that allow for the manipulation and modification of living organisms' characteristics. DNA is a long strain code consisting of four different molecules ATGC, a sequence of nucleotides e.g. ATGCATGGAT as shown in figure 46 (National Human Genome Research Institute, 2015).

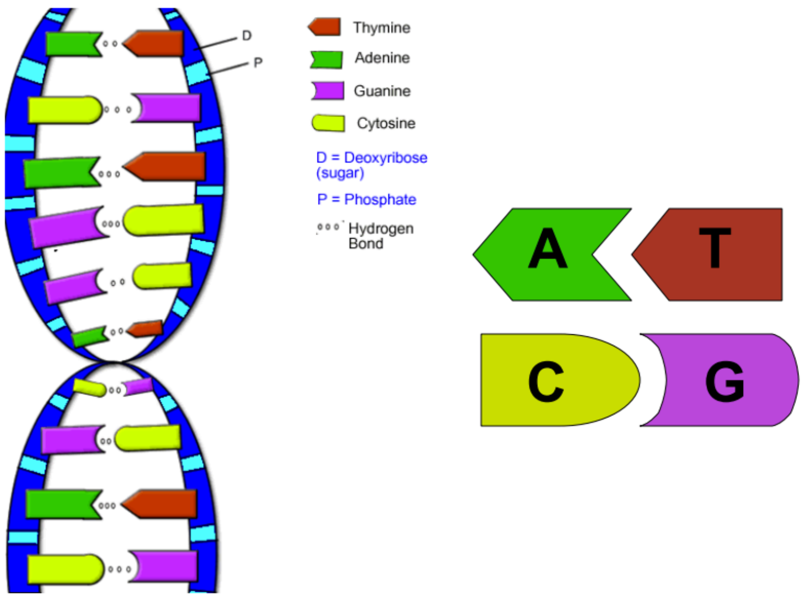


Figure 46 - The key characteristic of DNA, which leads to the double-helix structure, is how the two strands interact. Each of the four bases can only pair with one of the other bases; A can only pair with T, and G with C. (National Human Genome Research Institute, 2015).

These scientific developments made possible to draw the genetic map in order to create medicines and medical treatments to previously incurable conditions, amongst many other technological innovations (Ratledge & Kristiansen, 2001; Bryce Et Al., 2004). Similarly, this scientific improvement allows for the production of seeds that resist dry and poor land soils, for the modification of fruit, for adding resistance properties to plants against insects and plagues, amongst many other infinite applications (Bryce Et Al., 2004; Nair, 2008). This type of discoveries originated what is currently designated as Biotechnology.

> There are several definitions for Biotechnology. One simple definition is that it is the commercialization of cell and molecular biology. According the United States National Academy, biotechnology is the “controlled use of biological agents like cell or cellular components for beneficial use”. It covers both classical as well as modern biotechnology. More generally, biotechnology can be defined as “the use of living organisms, cells or cellular components for the compounds or precise genetic improvement of living things for the benefit of man. (Nair, 2008)

Biotechnology is a multidisciplinary science; it covers biology, chemistry, physics, genetics, microbiology, engineering, medicine, etc. It comprises processes that make use of biological agents to achieve products or substances of interest, in an intended way. It is commonly named as genetic engineering. Nevertheless, as a technology it exists for thousands of years, since the first agricultural societies started to collect the best seeds from each harvest to plant on the following year. Species crossbreeding is the oldest procedure of classical biotechnology along with the discovery of fermentation techniques by microorganisms (fungal and bacterial) in the production of bread, cheese, wine, beer, dyes, etc. (Uhlig, 1998).

> Archaeologists keep discovering earlier examples of the use of microorganisms by man. Examples of most of these processes date back to 5000 BC. Ancient Indus people, for example, prepared and used various types of fermented foods, beverages, and medicines. The ancient Egyptians and Sumerians used yeast to brew wine and to bake bread as early as 4000 BC. People in Mesopotamia used bacteria to convert wine in vinegar. Many ancient civilizations exploited tiny organisms that lived in the earth by rotating crops in the fields to increase crop yields. The Greeks used crop rotation to maximize crop yield and also practice various methods of food preservation such as drying, smoking, curing, salting, etc. All these techniques and processes were practiced in the Middle East and Southeast Asia including India. The Egyptian art of mummification used the technique of dehydration using a mix of salts. (Nair, 2008)

Theoretically, each living organism represents a strong source of potential bioactive substances ready to be tested and verified by the imagination of companies and scientists and that is the foundation on which biotechnology (and the actual research), as a scientific field, is built on (Bryce, Et Al., 2004), i.e encompassing all the products resulting from biological or genetic resources (all that is related to a living organism, e.g. a forest, a tree, the leaves, the branches, the fruits, the cells) consisting of biological material that comprises functional units of heredity (DNA) (Uhlig, 1998) that contain the structures transporting the genetic information, the responsible code for the production of hormones, venoms, enzymes, proteins, organs, anatomical structures, etc. (Ratledge & Kristiansen, 2001; Bryce, Et Al., 2004; Nair, 2008; Schmidt, 2012; Zhao, 2013). These genetic resources were known and used since the ancient times:

> The ancient people were also aware of the role of natural genetic resources such as plants in the economic growth of a land. The rulers at those times use to send plant collectors to gather prized exotic species of plants that produced valuable spices and medicines. Likewise, in modern times, colonial powers mounted huge plant collecting expeditions across Latin America, Asia, and Africa, installing their findings in botanic gardens. These early 'gene banks' helped the colonial powers to establish agricultural monocultures around the globe. (Nair, 2008)

The evolution from classical biotechnology to modern biotechnology involved only the usage of innovative tools to discover different and varied other functions of plants and animals, allowing for improvements on a new field of knowledge (Church & Regis, 2014). Transgenic and cloning are concepts defining modern biotechnology, differentiating it from classical biotechnology (Bryce, et Al., 2004; Nair, 2008; Church & Regis, 2014).

Modern biotechnology is a set of techniques from the biological sciences applied to market-orientated research and development. Through modern biotechnology, the gene, which is the functional part of the DNA containing the code for the production of a certain substance of interest, may be transferred to another organism, which will then start to produce higher quantities of this same substance (even though it has never produced it before) (Ratledge & Kristiansen, 2001; Church & Regis, 2014). This way, for instance, transferring a specific property from a plant that lives in a cold environment to a plant that is native to a warmer ecosystem allow for the latter to survive harsh cold winters (Bryce, et Al., 2004). The transferred characteristics allow for a greater, and higher in quality, crop as well as improved quality features of the plant. Similarly, the next figure (fig. 47) depicts the process for the production of genetic engineered insulin. The human insulin gene is spliced into the plasmid of harmless bacteria that will, then, start to produce insulin as by-product. This process enables for the production of large quantities of the substance, a reliable source to get insulin as it is of great demand for patients with diabetes (Bryce, Et Al., 2004; Puspari, 2012).

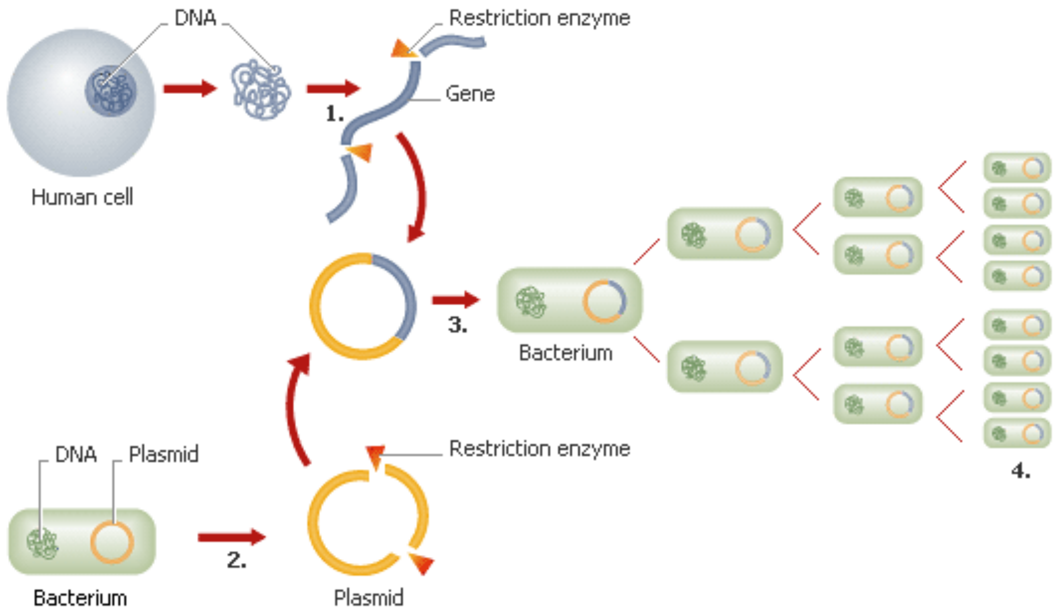


Figure 47 - The hybrid plasmid now contains the gene whose product (insulin) is desired. It can be inserted into the host cell, where it begins to function just like all the other genes that make up the cell. In this case, however, in addition to normal bacterial functions, the host cell also is producing insulin, as directed by the inserted gene (Lee, 2011).

3.1.1 Synthetic biology

> Circuitry, toggle switches, gates, sensors, oscillators. This is the language of component parts and manufacturing, of robots and computers and digital logic. It is not the language of life and death, of proteins tangles, evolution, reproduction and decay, the everyday struggles of biological matter. Yet this is now biology, albeit a new engineering approach to bioscience – the emerging field of synthetic biology (Ginsberg, Calvert, Schyfter, Elfick, & Endy, 2014).

According to the Syntheticbiology.org (Synthetic Biology Community, 2015), Synthetic biology refers to both a) “the design and fabrication of biological components and systems that do not already exist in the natural world” b) “the re-design and fabrication of existing biological systems". It is, in broader terms, combining engineering and biology (Church & Regis, 2014).

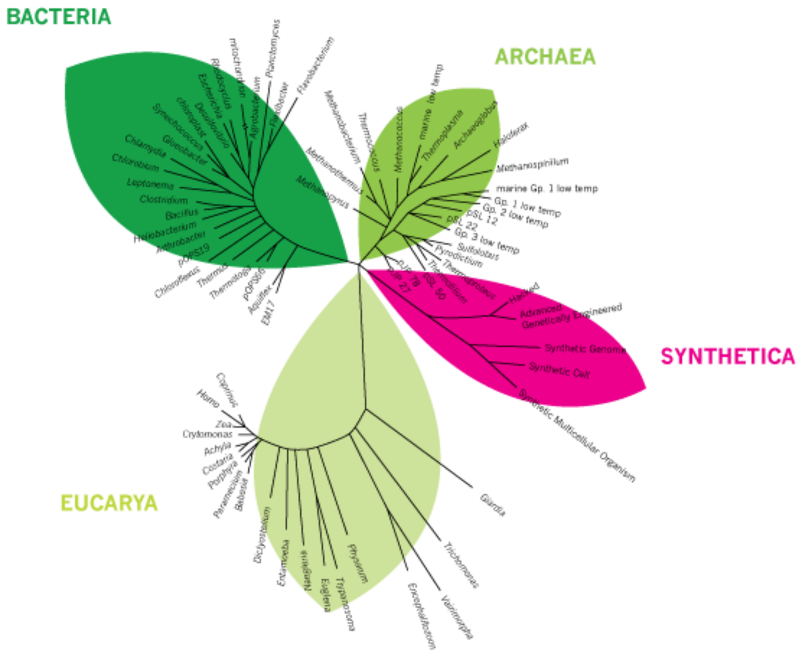


Figure 48 - The Tree of Life is always changing, ever since we first created it. Now, we are adding to the living kingdoms for the first time. But these synthetic organisms are no different to other life forms, except that we invented them. We will have to insert an extra branch into the Tree of Life. The Synthetic Kingdom is part of our new nature. (Ginsberg, 2010).

Synthetic biology is, in fact, the next step of genetic engineering, evolving to create entirely new living things as well as re-design existing life for new purposes. In genetic engineering, or genetic modification, the process is to remove genes from one species and insert them in the DNA of another, allowing for the creation of organisms (plants, animals, microorganisms) with new and improved features. The goal of genetic engineering was always the modification of an already existent organism. In contrast, according to Church & Regis (2014), synthetic biology assembles novel living systems (not found in nature) from a set of standardised genetic parts or biological components called BioBricks.

BioBricks standard biological parts are DNA sequences of defined structure and function; they share a common interface and are designed to be composed and incorporated into living cells such as *E. coli* to construct new biological systems, more as lego-like segments (e.g. systems, parts, devices) that can be assembled to create a new living system from scratch (fig. 49) (Church & Regis, 2014; Berk, 2014). Based on an existing bacterium, the first entirely synthetic life form was created in 2010 by the J. Craig Venter Institute, a single cell organism named *Synthia* (J. Craig Venter Institute, 2010).

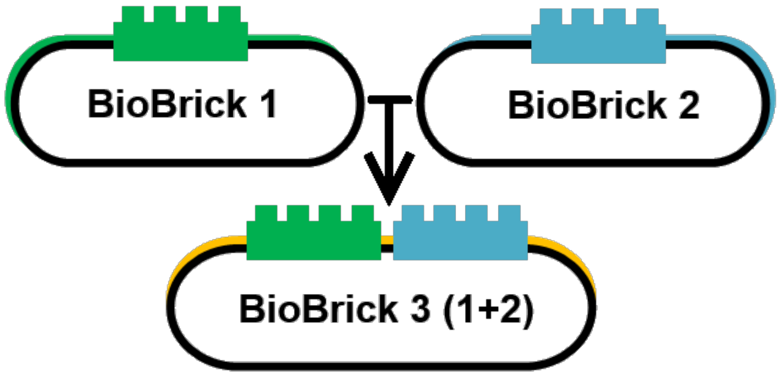


Figure 49 – BioBrick parts – standardised biological parts made from DNA – can be assembled using plasmids to make complex biological "circuits" (iGEM, 2013).

Bacteria are single celled microorganisms functioning with a simpler biological system, which is easy to alter. They are also abundant. Due to these characteristics, bacterium is often used as a vehicle (chassis) for the newly designed DNA.

As a highly sophisticated technology, mostly directed to achieve long-term sustainability, synthetic biology applications are varied. It is leading the way to help fixing several challenges this new century faces: problems like waste, medicines, energy, etc. Some of their applications include biomedicines (e.g. new drug for malaria treatment), biomaterials, biofuels, biochemical, etc. (Schmidt, 2012; Zhao, 2013; Church & Regis, 2014).

The cells may be thought of more like a factory, and genes as a program directing these cells to produce high value products; the possibilities of such technology are astounding, as noted by Alistair Elfick and Drew Endy (2014):

> Consider that the shell of an abalone, a large marine snail, is 98% calcium carbonate and only 2% protein but is 3.000 times stronger than a geologically constructed equivalent material, such as chalk. The key to this extraordinary strength is in the nanoscale precision of its manufacture with highly regular calcium carbonate tiles bound by protein glue. Within the tissues of the snail, molecular machines are made that possess the ability to capture a given atom and place it exactly where needed within a growing tile. If we could borrow the manufacturing skills of the abalone and combine these with the light-harvesting properties of plants, maybe we would produce an organism that could make new super-strong building materials with nothing more than sunlight and seawater (…)

> with synthetic biology, we can harness the machinery to make those molecules such that we don't need to go destroying the planet's ecosystems to harvest them. (Ginsberg et al., 2014).

These aforementioned aspects are essential to what the actual study intends to convey. One of the suggested approaches, discussed in this dissertation, to create alternative scenarios for the damaging current production and manufacturing processes is the engineering of microorganisms to produce potent textile dyeing material, in order to achieve a further balanced resilient development. The present study argues that, projecting products, such as textiles or garments (or textile materials), incorporating knowledge from the biological sciences in the creative process of design is vital when considering and planning the lifecycle of goods (any goods); it is key for a further sustainable design of textiles, i.e. dyes, fibres, etc., and, as discussed later on, the enhancement of lifestyle in general without compromising commercial profit.

The textile industry, being one of the major pollutant sectors on the planet, need to embrace all possible alternatives, even though some might represent or encompass radical forms of approach. This is especially relevant due to the fact that its related sustainability problems are much more vast than only the depletion of resources or water contamination; the sector faces issues such as great expectation from consumers to brands, economic crisis threatening sales, low budgets to fund projects or improve systems, and so on (Appendix B).

4. Sustainability

4.1 Sustainable thinking

Globalisation has many advantages - increased cultural intertwining (thus more acceptance and social tolerance), higher flow of information, vast market enabling production, and so on. However, massive manufacturing has also created a set of consequences that must be addressed urgently. One massive challenge within our society resides in the over-consumption of natural resources, caused by the uncontrollable demand for goods (Clarke & Steinle, 1995; Klein, 2000; Bendell & Kleanthous, 2006; Nilsson, 2007; Fletcher, 2008; El-Hagar, 2010; Mulveney, 2011; Greenpeace, 2011; Greenpeace, 2012; Greenpeace International, 2012; Malik, Ghromann, & Akhtar, 2014).

The expected harmonious relationship between humans and nature has been decreasing shockingly, particularly since the industrial revolution; the depletion of irreplaceable natural resources is causing huge damage to the whole ecosystem. Not only are we destroying nature but, additionally, we are removing ourselves from it in the process.

Until fairly recently, manufacturers focused their attention on industry elements that would enable quick profit (maintaining the cost of production low) risking efficiency and quality in general jeopardising, simultaneously, the basic values of life and the future (and the present), i.e. a balanced planet and sustainable development. Meanwhile, the problematic aspects related to the inadequacy, at the sustainability level, are steadily being exposed and debated. Furthermore, legislation is increasingly emerging as demanding; pollution control boards are continuously restricting guidelines for several manufacturing sectors (Ellen MacArthur Foundation, 2012). This is particularly relevant in regards to the textile industry, one of the greatest pollutants in the world.

The most popular definition of sustainability is that from the *Brundtland Report* of 1987 stating "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"

(Mulvaney, 2011, p. 42). Less vague, more practical definitions advocate that sustainability has to be seen through three different lenses – the principle of the three pillars of sustainability. The three pillars of sustainability principle asserts that for a complete sustainable development problem to be solved all three pillars of sustainability must be sustainable; the three pillars being social, environmental, and economic sustainability (fig. 50) (Mulvaney, 2011; Kruschwitz, 2012). This means that economic activity is embedded in a social and political context, which is, in turn, embedded in the world's ecosystems upon which all life depends (fig. 51); in short, a model considering profits, planet and people. As Jason Jay (2012) defends, societies can only be sustainable when capable of meeting basic criteria, assuring consumers that "renewable resources aren't used faster than they can be regenerated; pollution and wastes are emitted no faster than natural systems can render them harmless" (Kruschwitz, 2012).

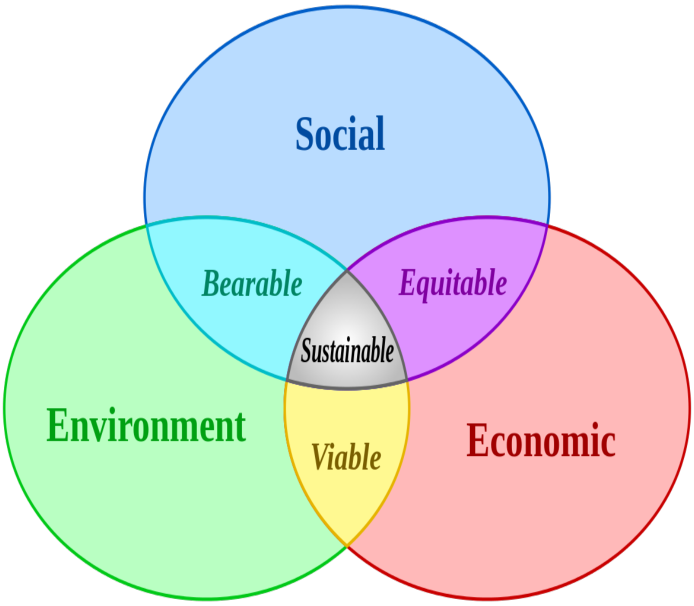


Figure 50 - Sustainable development as perceived through the three pillars of sustainability principle (Wikipedia, 2006).

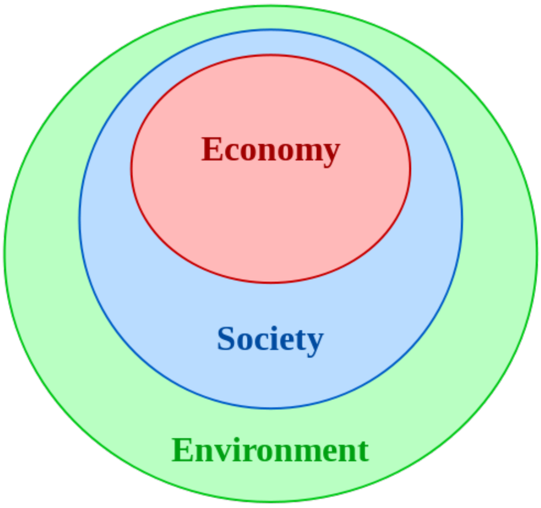


Figure 51 - A diagram indicating the relationship between the "three pillars of sustainability", in which both economy and society are constrained by environmental limits (Wikipedia, 2011).

One major problem within the textile sector, especially in the fashion design domain, is the fast pace in which its foundation is based, feeding unfulfilled desires through consumption, every season; the short cycles of the traditional fashion industry need to be considered, revised and redesigned, since, from a sustainability perspective, it is not beneficial (Earley & Goldsworthy, 2015). Another nuisance is the lack of deeper elements of value (e.g. high ethical standards, low impact manufacture, efficient use of materials, clean methods of production), neglected by most of the textile industries (Fletcher, 2008; Andersen & Earley , 2014).

On the other hand, one of the most substantial cultural shifts witnessed in the recent decades past has been the increased awareness over both social and environmental issues. Businesses are slowly realising that a fast change is required and indispensable in their dynamics, as it is no longer sustainable, at the economical level (Ellen MacArthur Foundation, 2012), to not engage with a growing new market, fully conscious of the implications of a "broken capitalist system" (Foxley, 2011).

This new emerging market is characterised by mainstream consumers, increasingly aware, concerned over social wellbeing and the significance of ecological footprint reduction. These consumers are observing brands, questioning providence, voting with their currency, "adopting a *make, do and mend, waste not, buy not* mentality" (Steffen, 2006). These are costumers that, ultimately, need to feel assured that their money returns to the people, through design that is prepared to sustain communities, encourage social equality, promote local employment and, simultaneously, nurture the environment (Bendell & Kleanthous, 2006).

This consumer's behaviour has real repercussions at different levels as it challenges businesses and pushes them to operate, to look not only into finance but also into people and environment (Foxley, 2011; Ellen MacArthur Foundation, 2012).

Regarding textiles in general and the creative process related to it, it is most important that in the creation of a future product (Excellency intended) a valid plan has been put to action by designers or business plans and frameworks, i.e. a strategy born from deep consideration of all aspects and stages of a product's lifecycle (e.g. *circular economy*) (Ellen MacArthur Foundation, 2012). It is the responsibility of all the textile industry professionals, including designers, to provide for good design - resilient in all forms, with a balanced and restored world in mind. Given the vast array of issues surrounding the textiles sector and given, above all, that sustainability problems are no longer only associated with climate change, it is of significance that design embraces all the technological innovations currently emerging by exploring their possibilities and, maybe, their implementation. Knowing what is available will utterly play a major role in making a difference. Fashion field, especially, is a social phenomena, it mirrors, supposedly, the society in which it is embedded, in all its facets, e.g. culturally, politically, religiously and technologically. There are, presently, technologies that are still unexplored by the industry of textiles, albeit the challenges that need imperative resolving.

Challenges are deeply connected to finance and transformation paradigms and, as mentioned above, with the great expectation of brands by consumers. The society moves in an increasingly faster pace, and so expectations. This century is characterised by a fast culture, and one of evolution, adaptation and change. To operate in and around it is crucial to grasp the real and different kinds of values attached to contemporary products, and to deeply understand their lifecycle (Ellen MacArthur Foundation, 2012).

Sustainability in textile design is therefore closely related to, not only the reduction of its ecological burden proved to be damaging but also, the consideration on how to provide wellbeing, equality and social improvement through products (Appendix B).

This dissertation intends to propose new strategies for a sustainable development by the incorporation of scientific advancements, however, it is also of great reflection and implication that these, or design in general, gets to be communicated in a highly efficient manner; in a way that allows consumers to understand, select and choose a more ethical lifestyle, buying products they really want to keep. Figure 52, for instance, is an advertisement to an apparel company called Patagonia. Patagonia has decided to go “beyond the bounds of normal operations to communicate and create new orders of value for a wider customer base” (Foxley, 2011). In the campaign *Don’t buy this Jacket* consumers are made aware of the ecological impact of the brand’s products so that they can make a responsible decision at the time of the buy; consumers may consider on how much they really need a specific piece of clothing when confronted with the environmental footprint of their wishes.

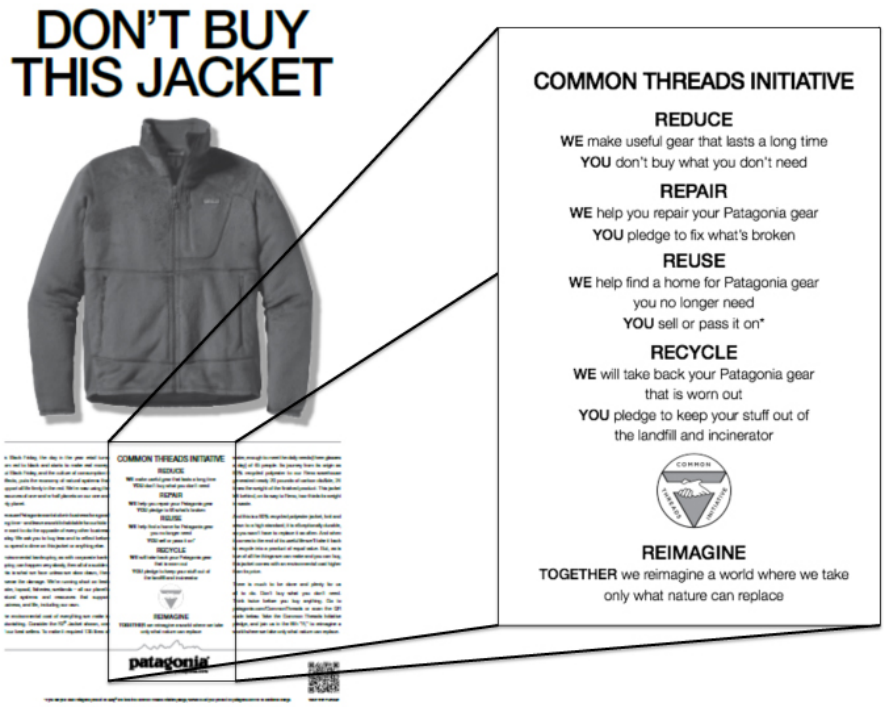


Figure 52 - Patagonia's "Don't Buy This Jacket" advertisement; a campaign attaching elements of value to their products (Kruschwitz, 2012).

Gradually, companies are adopting a conscious, attentive and critical position towards sustainable issues, integrating human wellbeing and green philosophies at the core of their corporate identity (Bendell & Kleanthous, 2006). Textile brands are slowly providing design that represent local production, raw materials such as natural dyes or fibres and traditional know how by producing and resourcing locally (Coen, 2012).

Corporations, brands and manufacturers are the ones with the power, and the responsibility, to boost the masses towards sustainable consumption “by editing consumer choices through product design, distribution and marketing; and by influencing how, when and for how long consumers use their products" (Bendell & Kleanthous, 2006, p. 2; Ellen MacArthur Foundation, 2012). Besides, it makes sense that a sustainable economy should first arise from corporations, as they are the major consumers of resources (and the beneficiaries). Truth is, "if you don't have an environment you don't have an economy" (Blue & Green Tomorrow, 2011). Alas, products integrating, simultaneously, culture, communities, environment, economy, green technologies and sustainable materials are, still, a real challenge.

4.1.1 Green philosophy

Design philosophies, or disciplines, embracing the nature approach include Biomimicry, Getting to Zero Waste, Resilience Engineering or Cradle to Cradle.

Figure 53 – Biomimicry, (from bios, meaning life, and mimesis, meaning to imitate) getting inspired by nature's design (Biomimicry Institute, 2010); (Sheppard, 2010).

Biomimicry is "a design discipline that seeks out sustainable solutions by emulating nature's time-honoured patterns and strategies" (Sheppard, 2010). It considers three tenets: nature has to be followed as a mentor, seen as a measure and serve as inspiration in design. The main idea is that nature has already solved many of the issues society is currently struggling with - energy, food production, climate control, non-toxic chemistry, transportation, and packaging (Biomimicry Institute, 2010). Designers take advice from biodiversity by learning and understanding the proper know-how behind its magnificent designs, shaped through millions of years of evolution/existing and adapting to natural changes.

> Consciously emulating Nature's genius means viewing and valuing the natural world differently. In biomimicry, we look at Nature as model, mentor, and measure: Model: Biomimicry is a new science that studies Nature's models and then emulates these forms, processes, systems, and strategies to solve human problems – sustainably. Mentor: Biomimicry is a new way of viewing and valuing nature. It introduces an era based not on what we can extract from the natural world, but what we can learn from it. Measure: Biomimicry uses an ecological standard to judge the sustainability of our innovations. After 3.8 billion years of evolution, Nature has learned what works and what lasts. (Benyus, 2002, p. 1)

Figure 54 - Stefanie Nieuwenhuyse's dress made of discarded wood chips is a luxurious sustainable garment using nature's natural patterns and shapes – inspired by biomimicry. The approach combines modern techniques such as laser cutting with hand-sewn details, using discarded pieces of plywood and cutting the shapes out as efficiently as possible, and applying them on the fabric. This process is both sustainable as it is resilient (Mok, 2011).

Relatedly, the *Cradle to Cradle* approach is to consider the way we have been designing products. As stated by Braungart & McDonough in *Cradle to Cradle - remaking the way we make things* (2002), their manifesto for a radically different philosophy and practice of manufacture and environmentalism book, “waste equals food". This is one of the three responsible design principles the book communicates along with the two other principles – solar income and celebration of biodiversity. The authors explain how products can be designed from the start so that, after their useful lives, they will provide nourishment for something new. They can be conceived as biological nutrients (that will easily re-enter the water or soil without depositing synthetic substances or materials and toxins) or they can be technical nutrients that will continually to circulate as pure and valuable materials within closed-loop industrial cycles, rather than being recycled or downcycled into low-grade materials and uses (Braungart, McDonough, & Bollinger, 2007).

With slight differences between the varied approaches, it is clearly that the principles behind are bind together with nature's inspiration, respect and protection as well as an eagerness to change the world's view on how to develop products around us. However, as Myers (2012) refers in his book *Bio Design: nature, science creativity*, these "biology inspired approaches to design and fabrication are popular but frustratingly vague green design". He continues by stating that biotechnology applied to the design field is a neater approach because it "goes beyond mimicry to integration"; biotechnologies applied to fabrication not only refer to the replacement of industrial or mechanical systems with biological processes but also to the "incorporation of living organisms as essential components, enhancing the function of the finished work" (Myers, 2012).

As emphasised above, responsible design landscape must be shaped through the rigorous analysis of a product lifecycle; considering, understanding, and debating, the way a product impacts on lives and the planet. Reducing the environmental footprint of industries and preserving biodiversity patterns and health (as well as guaranteeing the wellbeing of humans) are certainly subjects that must be envisioned in radical solutions offered nowadays by science. The possibilities of biotechnology are increasing as the development in science is progressing. Some strategies or methods represent a massive change on manufacturing goods, since, until now, all forms and alternatives to tackle the biggest sustainable issues are not as effective as desired.

> Eco-efficiency is an outwardly admirable, even noble, concept, but it is not a strategy for success over the long term, because it does not reach deep enough. It works within the same system that caused the problem in the first place, merely slowing it down with moral proscriptions and punitive measures. It presents little more than the illusion of change. (Braungart & McDonough, 2002, p.62)

Once again, challenges within the textiles and apparel industry are not only about material exploitation and depletion of resources anymore but, rather, working in such a fast, demanding and complex society; companies in a competitive environment, having tight deadlines, problems communicating, and the shadow of an economic crisis threatening commercial success, or causing limited budgets to improve already implemented systems and established practices (Appendix B). Fighting these aspects through science and technology may help to boost social innovation or improve lifestyle in general without compromising commercial profit (Ellen MacArthur Foundation, 2012). The textile industry, being one of the major pollutant sectors on the planet, need to consider all that is at stake and embrace unexplored technologies and investigate possible alternatives, even though some might represent or encompass radical forms of approach to oppose implausible systems.

According to Garcia-Serna, Perez-Barrigón, & Cocero (2007), this new century is forcing many changes, and one must "develop novel guidelines, methods and procedures for design and innovation towards sustainability" (Ellen MacArthur Foundation, 2012).

In sum, textile and clothing industries must create and develop strategic, tactical approaches to the design process e.g. designing long life or smart materials, projecting products for a *circular economy*, upcycling, etc. It is necessary to understand in greater depth different concepts and ideas and analyse how far they are from the market (or how much investment they need). Biotechnology is key, especially when approaching design industrial processes. Bio-based innovations have a significant role in sustainable development goals that embody economic requirements as well as ecological and social ones. Many varied studies, including the reports from the Organization of Economic Cooperation and Development (OECD), concluded the application of scientific and technical advances in life science to develop commercial products (biological technologies) is route to sustainable design (OECD, 2013).

4.1.2 The biological approach

Along with sustainable strategies proposed by green philosophies, further biotechnological-based methodologies are reported to have increased in the last two years and are starting to be considered in the creative process; Myers (2012) points out:

“designers and artists have always looked to nature for inspiration or materials, but only recently have they been able to incorporate living organisms in their work. In a world of finite resources, design that appropriates sustainable templates from nature is likely to prove as vital as it is novel”. According to Isaacson (2011), in his book about Steve Jobs biography, Steve Jobs states that he believed biology-based technologies were the next following revolution - “The biggest innovations of the twenty-first century will be the intersection of biology and technology. A new era is beginning” (Isaacson, 2011). Aiming towards solid sustainability, biotechnology explores many alternatives to achieve it; the emerging field of synthetic biology is one discipline that is creating radical changes that can truly affect the way products are designed. The extent to which textiles sustainable design benefit from the incorporation of science subjects in the creation process or manufacturing of goods must be object to great analysis (how does design relate to the biotechnology fields, and until what degree can responsible design benefit from the incorporation of living organisms in its creative process?) Moreover, further discussion is critical to understand the ways through which textiles may deliver quality via biology.

As the issues on sustainability are not only related to resource depletion but also the integration of social innovation drivers and the enhancement of wellbeing in the creation of goods, the symbiosis between technology and design are utterly crucial, particularly in the present day. The increasing trend of biotechnological materials or products in the field of design is an example that, slowly, society is changing into conserving and accepting that the industrialised world needs a new plan to start building products in a healthy, qualitative way as defended by Braungart & McDonough (2002) in their book *Cradle-to-cradle*. The collaboration between scientists and designers play a vital role as it strengths the results for the quest of effective sustainable design of materials and products.

The advantages of biological approaches are varied in the textile field. Processes of bioremediation through microorganisms or even the usage of natural ancient dyes are established and well known in the industry. But there is more to the usage of microorganisms through the advancements of modern biotechnologies or simply through acquiring further knowledge on biodiversity and its potential, as discussed below.

4.2 Designing with nature

The scope of science currently allows for a completely new radical way of producing materials or for innovative methods of creation. With increasingly more technological innovation and scientific breakthroughs as well as collaborations between scientists and designers the world has been noticing for the past couple of years the intensification of biotechnologies as the foundation of many sustainable design projects (Myers, 2012), supporting what this dissertation suggests.

Collaborations between science and design have been evident in many varied exhibitions, from architecture to art and design, particularly for the past two years (e.g. Exhibitions "En-vie" or "Grow your own") (Myers, 2012; En-vie/Alive, 2013; Science Gallery, 2013). Biotechnology applied to these varied fields contributes not only with innovative designs and solutions to our daily challenges but also to grow awareness about the importance of conserving the biodiversity. They depict a varied range of projects (real or speculative) that presents highly sustainable products whilst provoking consideration and debate through the use of the biology approach in creation. These projects involve living organisms at all scales - animals, plants, microorganisms (bacteria, fungi, algae), cells, etc. that can be used to build, influence and improve the objects around us. Understanding these methods and the potential impacts of biotechnology on the world also helps to observe how society is evolving. The next projects are important to realise the infinite and astounding possibilities of biology-based methodologies.

In the next example (fig. 55), a project featured in the highly acclaimed book *BioDesign – nature, science, creativity* is presented. It is named Biobrick and is particularly interesting to the architecture field professionals. Although the many positive aspects of traditional concrete bricks, their ecological footprint is still significant. Biobrick explores the microbial activity performance and sand to create sustainable bricks; bacteria is able to glue the grains of sand together through a process that uses calcium chloride and urea to stimulate microbial induced calcite precipitation, forming grains of sand into stone.

Figure 55 - The vast majority of the brick production worldwide is in India, China and Pakistan where energy-intensive, traditional techniques and severe labour dominate. BIOBRICK project proposes an alternative that is more sustainable as it is made through bacterial activity at room temperature (MoMA, 2012).

Similarly, the speculative project Dune (fig. 56) uses the same microbial activity technique approach (microbial induced calcite precipitation) to construct biologically. With desertification control in mind, Dune's goal is to form a protection barrier by injecting convenient areas that would then turn into sandstone as depicted in the figure above.

Figure 56 – Project DUNE: sand solidified by bacteria and shaped by the wind, eventually allows water to accumulate and forms a barrier against the spread of the desert (MoMA, 2012).


Figure 57 – Microbial home (MoMA, 2012).

Microbial Home is a concept that covers extraordinary several home appliance units as shown in figure 57. The main one is basically a kitchen island called Methane Bio-digester. Bacterium digests organic matter from the waste disposal piece generating methane, which is then used to power other units or lighten the space as demonstrated in figure 58.

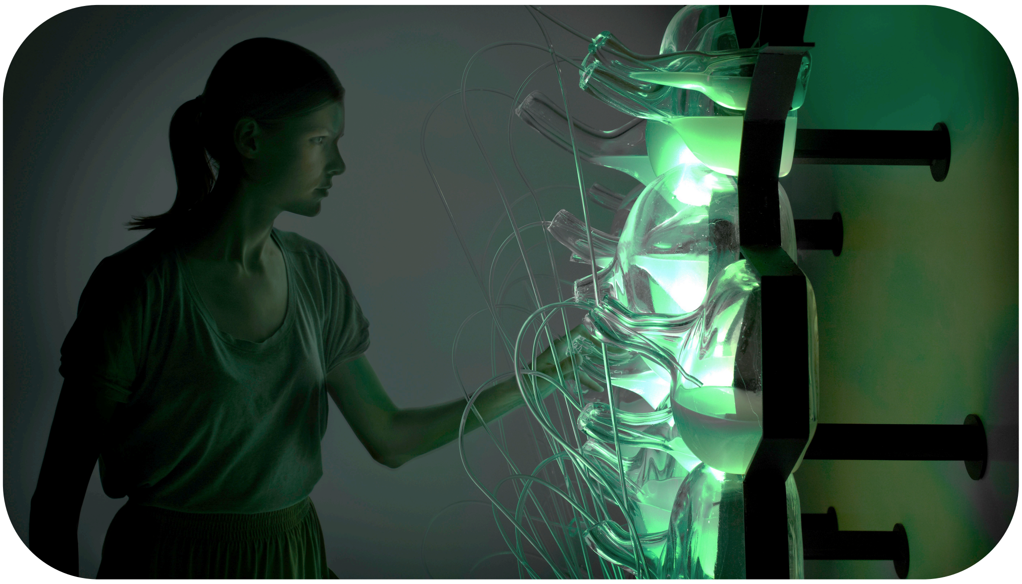


Figure 58 - BioLight (Philips, 2011).

Yamanaka Furniture project, showcased in Paris in the "Alive/En-vie" exhibition, in 2013, displays a chair built through fungal activity (fig. 59). The mechanism behind this piece of furniture is very basic – material grows by infusing live fungal cells into sawdust. The sawdust acts as cellulose based medium, which serves both as nutrient and framework for the living organism to grow on. After solidifying it becomes a lightweight and strong material.

Figure 59 – Fungal tissue will bind, solidify and harden into any chosen form, and, once dried out and processed, becomes a lightweight and strong material. Photo: (Alive/En Vie, 2013)

At the same exhibition varied sorts of objects such as 'honey bee-sculpted' vases, depicted in figures 60 and 61 can be found. As the author, Tomas Liberty, states:

> The material comes from flowers, as a by-product of bees, and in the form of a vase ends up serving flowers on their last journey. The fragile and seemingly ephemeral result stands in a stark contrast with its durability and resistance. In fact, Vessel #1 has the potential to last over 2,000 years. Honeycombs containing edible honey were found in Egyptian pharaohs' tombs" (En-vie/Alive, 2013; Libertiny, 2013).

Figure 60 – Vessel #2 (Libertiny, 2013).

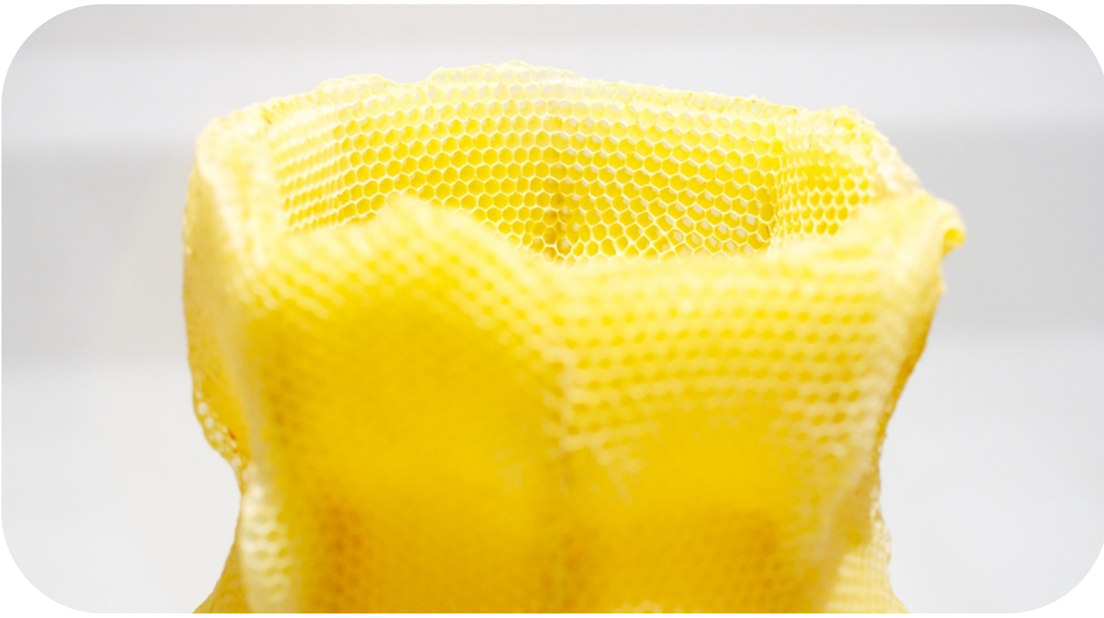


Figure 61 – Detail of Vessel #1 (Libertiny, 2013).

Analogously, textiles can benefit from the use of living organisms to produce and develop materials. The project entitled Biocouture (fig. 62) is one of the most known examples of biotechnology applied to the developing of sustainable textile materials. Rather than exploiting plants or petrochemicals to provide the raw material for fabric this project represents a new form of textile produced only through bacteria. These microorganisms will spin micro fibrils of pure cellulose during fermentation, which form a dense layer that can be harvested and dried.

Figure 62 - In its raw state this surface is amber colour and is very similar to human skin. When it's dry its texture is identical to vegetable leather (Lee, 2009).

> To a sugary green tea solution we add a mixed culture of bacterial cellulose, yeasts and other microorganisms to produce a flexible cellulose mat. The bacteria feed on the sugar and spin fine threads of cellulose. As these start to stick together they form a skin on the liquids surface. After two to three weeks, when it is approximately 1.5cm thick, we remove the cellulose skin from the growth bath. We can then either use it wet to shape on to a 3D form, like a dress shape, or dry it flat and then cut and sew it into a garment. (Lee, 2009)

Akin to BioCouture, the project Micro'be (fig. 63) follows the same type of methodology - classical biotechnology at its core. Micro'be investigates the practical and cultural biosynthesis of clothing - to explore the possible forms and cultural implications of futuristic dressmaking and textile technologies. Instead of lifeless weaving machines producing the textile, in this case, living microbes will ferment a garment - will not only rupture the meaning of traditional interactions with body and clothing but also raise questions around the contentious nature of the living materials themselves (Franklin & Cass, 2011).

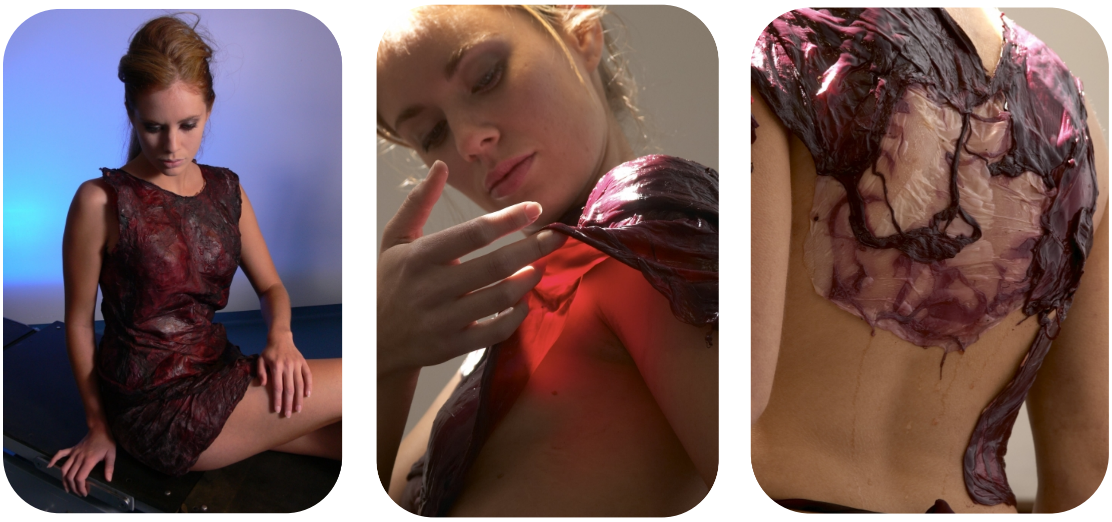


Figure 63 - Red material around the sides of the top is cultured from red wine. The Amber-opaque material insert is cultured from beer. The ultimate goal of the *Micro'be'* project will be to create a seamless, bio garment that forms without a single stitch (Franklin & Cass, 2011).

(In)Visible Membrane (fig. 64) is a study that explores the life on the human body and its design applications – converting invisible bacteria found on the human body into a visible form. It confronts scientific data and methods with fashion design in order to find a balance between individual identity and the surrounding local environment, creating a second layer (Baumel, 2009).

Figure 64 – (In)Visible Membrane - So far we only know 2-3% of our skin bacteria. For ten years, microbiologists have known that bacteria communicate with molecules through a chemical language. What if a communication layer could grow on our skin, which would recognize and interpret these molecules? (Baumel, 2009)

These examples not only illustrate how microbial activity is playing an important role when thinking elements of architecture, art or design but how accessible, surprising and extraordinary results can be achieved through biotechnology. Lastly they represent a manner of building or creating things that relate harmoniously with nature and its natural processes.

The assimilation of science in textile design allow for rather audacious projects indeed, particularly in a time where the advancements of modern biotechnology (with disciplines like synthetic biology) are increasing and becoming vital for the incorporation of sustainability thinking in the design field.

The following project, illustrated below in figure 65, also combines the expertise of designers and scientists. BioLace is a speculative study on the possibilities of engineered plants through hybridisation via synthetic biology. Plants are reprogrammed into multi-purpose factories, possessing the ability to deliver, simultaneously, enhanced food and woven, laced fabric from the roots.

This type of project helps to question the potential of living organisms as technologies and the consequences of incorporating sophisticated science at the core of creative sustainable processes.

“Could biological engineering promote a new kind of sustainable textile manufacturing, less reliant on chemicals and less energy-hungry than our current models of production?”; “Would you eat a vitamin-rich black strawberry from a plant that has also produced your little black dress?” (Alive/En Vie, 2013). This approach enables for a new radical way of rethinking materials as it consists in building new biological functions or systems or re-designing existing natural ones (Synthetic biology org). The production of biomaterials is a significant impact of this technology (Schmidt, 2012).

Figure 65 - Biolace (Alive/En Vie, 2013).

E-chromi (fig. 66) is another project that applies the emerging field of synthetic biology; it explores the possibilities of engineered bacterium *E-coli* to monitor diseases.

Ingested as yogurt it is programmed to secrete pigments visible to the naked eye should toxins be sensed in the gut. The Scatalog briefcase's contents suggest an alternative aesthetic for biological computing with the human gut as interface, and outlines a future where, through synthetic biology, disease monitoring has become a cheap, personalised, consumer product (Ginsberg, 2009).

Designers are considering science as a part of the creative process, able to generate unique and often surprising results (En Vie, 2013; Grow your own, 2013), offering a fresh perspective on how to manufacture things. Cut edge and complex technologies serve better the apparel industry in terms of quality innovative garments. Although most technology is underexplored, the recent trend of extensive use of biomaterials in product and fashion garments is growing exponentially, given their possibilities of resilience.

The latter examples perfectly illustrate the importance and increased role of biotechnology in the textile field and in the design process, contributing with smart, ecological and resilient materials. Furthermore, it represents an exploration on the aesthetic value of sophisticated technologies and their results.

Figure 66 – The Scatalog: in 2009, cheap, personalised disease-monitoring works from the inside out. Ingested as yoghurt, E. chromi colonise the gut. The bacteria keep watch for chemical markers of disease, producing an easy-to-read warning signals to prompt you to see the doctor (Alive/En Vie, 2013).

The increased number of projects, with principles of biological approach, also reveal that its application is achieving great significance, standing out as innovation and front forward thinking in the pursuit of answers to present concerns or setting new boundaries for higher quality value products. Questioning the practises currently established illustrates, on the other hand, the several aspects concerning the designer's view on the subject, his interpretation of modern society, and his conduct given the challenges.

5. Sustainable dyeing

5.1 Responsible textile dying

The complex issue of textile dyeing, and the need to incorporate sustainable drivers at the core of the industry, focused this research on the study of greener alternatives as opposed to the current dyeing processing methods of textile industry.

Synthetic dyes possess many advantages, however, some of them are being prohibited through association with toxicity and environmental concerns. Natural dyes, representing a much lower risk, have been re-introduced to the market, employed to accomplish ecological textile products. Although their many advantages, it is accurate to say, as described in 2.3.3, that their extraction is somewhat difficult and costly, reason enough to consider other alternatives (no dyeing processes involved) or the application of dyes obtained from different biological resources, via both classical and modern biotechnology (microorganisms producing biodyes). Natural dyes do not always deliver great dyeing in terms of colourfastness, however with critical expertise these issues can be overcome. Further acquaintance on the existing biodiversity (potentially able to provide textile dyes), additional knowledge on application recipes as well as existing innovative techniques of fixing dyes to fibres (e.g. ultrasound fixing techniques, waterless technologies), are most significant in regards to the sustainable dyeing subject. Equally, however, the advancements in the biotechnology field and its appropriation by the sector are vital to its effectiveness and to the decrease of pollution and contamination. Still in this regard, the use of microorganisms, such as bacteria, microalgae and fungal, is already known to this industry for their bioremediation qualities; microorganisms have been, in the recent past years, associated with biodegradation of dyes from industrial effluents. This is a process highly regarded as an eco-friendly alternative for textile effluent treatment. But there is more to these living organisms as examined later on, in 5.1.2, when assessing biodyes possibilities as an alternative to aid sustainable dyeing process.

Regarding energy and water waste, innovative waterless dyeing techniques have been developed and introduced. These technological developments are believed to cut the usage of water to nearly zero which means that the "quantity of chemicals is drastically reduced, while faster dyeing cycles lead to a major drop in energy consumption" (Heida, 2014). These innovations, therefore, represent a genuine achievement towards a further efficiency in the dyeing industry in regards to sustainability, since it significantly reduces the ecological footprint of dyeing practices. There are three companies that implemented waterless dyeing technologies in the past couple of years, two American ones – ColorZen and AirDye -, and a Ducth one – DyeCoo (Dyecoo, 2010) (AirDye Solutions, 2014; ColorZen, 2014; Heida, 2014).

5.1.1 Natural coloured fibres

Many textile products are free of dyes; the fibres are naturally coloured with no requirement for finishing processes such as dyeing. Albeit limited tones, this is true for certain species of cotton, silk or even wool.

Figure 67 – Natural coloured cotton (Fox Fibre, 2012).

Coloured natural fibres, such as cotton (above, fig. 67), are the result of years of hybridisation via classical biotechnology, whilst others, such as the Golden Orb-Weaver silk (fig. 68), are simply naturally pigmented. Some other fibres or biological resources may be genetically modified in order to hold these properties.

These naturally coloured fibres do not need to be dyed, which is a major advantage in regards to pollution. Natural coloured cotton, aside saving all the costs and waste related to dyeing procedures, has the benefit of having highly protective properties against Ultra Violet Rays (Hustvedt & Crews, 2005). Natural coloured cotton is also resistant to change as compared with the conventional dyed white cotton. In flat contrast, after laundering, the colour becomes stronger and more intense (Fox Fibre, 2012).

Some silk fibres also possess natural pigment in their mass or structure; the spiders Orb-Weaver from Madagascar not only produce one of the strongest materials in the world but also a fibre possessing a natural pigmentation; the golden colour is natural and no treatments or dyes were used in the making of the apparel (fig. 68) (Levene, 2012).

Figure 68 - Natural coloured golden cape displayed at the Victoria & Albert Museum, London. It is made of silk obtained from Golden Orb-Weaver spiders, collected on the highlands of Madagascar (Jones, 2012).

In order to produce other types of coloured silk, experiments were conducted on ordinary silkworms through genetic modification or simply by manipulating their environment (Chen, Wang, Hua, & Du, 2007). In figures 69 and 70, silkworms are fed mulberry leaves sprayed with dyes. In figure 69, silkworms are given a mixture of mulberry leaves and fluorescent dyes; the dye molecules become part of the silk filaments producing permanent luminescent hues (Cartwright, 2011; Meinhold, 2011). In figure 70, mulberry leaves are sprayed with red fabric dye; silkworms absorb the red dye through digestion and produce pre-dyed pink silk threads (Diep, 2013).

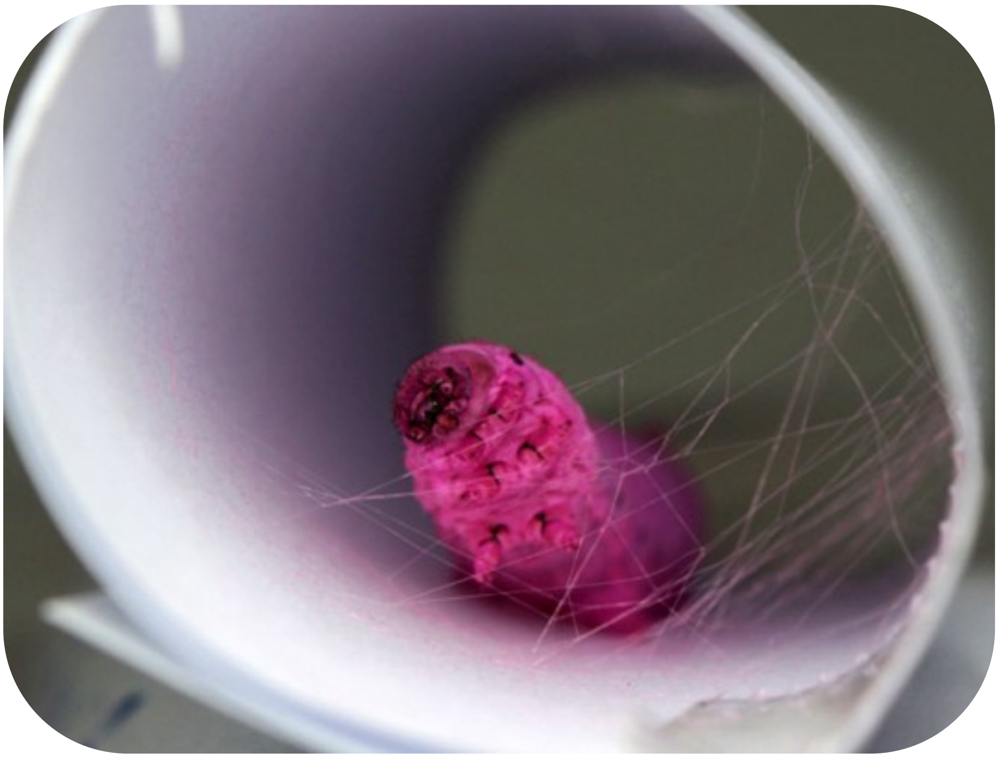
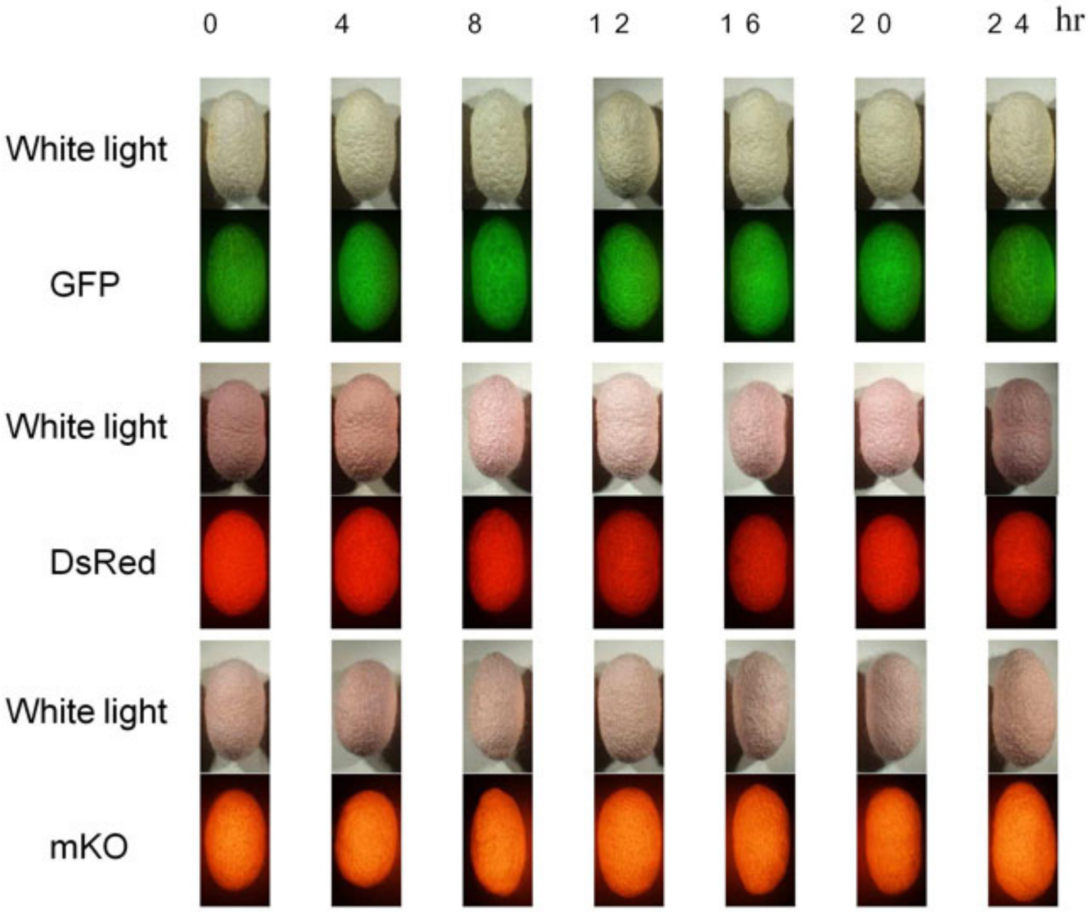


Figure 69 - Intrinsically coloured and luminescent silk (Meinhold, 2011).

Figure 70 - Uptake of azo dyes into silk glands for production of coloured silk cocoons using a green feeding approach (Diep, 2013).

Similarly to the two formers examples, however employing tools from modern biotechnology, transgenic silkworms are able to create fluorescent proteins derived from the DNA sequences of other organisms (*Discosoma* corals, *Fungia concinna* coral and jellyfish producing red, orange and green glowing hues, respectively) (Zimmer, 2013). The commercialisation of materials such as luminescent silk fibre is particularly significant for the medical field (Cartwright, 2011). The next table shows the coloured luminescent silk cocoons:

Table 5 Green, red, orange glowing hues produced by silkworms (Zimmer, 2013)



Alpaca wool (fig. 72) is very versatile and considered a top quality fibre because of the many properties it possesses; it is soft, resilient, silky, hypoallergenic, etc. Additionally, it has excellent thermal properties and it is warmer than other types of wool. Nevertheless, amongst all the amazing characteristics this type of wool holds, one of its greater features is the vast variety of shades it provides. Alpaca wool offers the most diverse coloured natural fibres on the market, with sixteen official colours that can be sub-divided in many other subtle shades and hues (Alpaca Owners Association Inc., 2015).

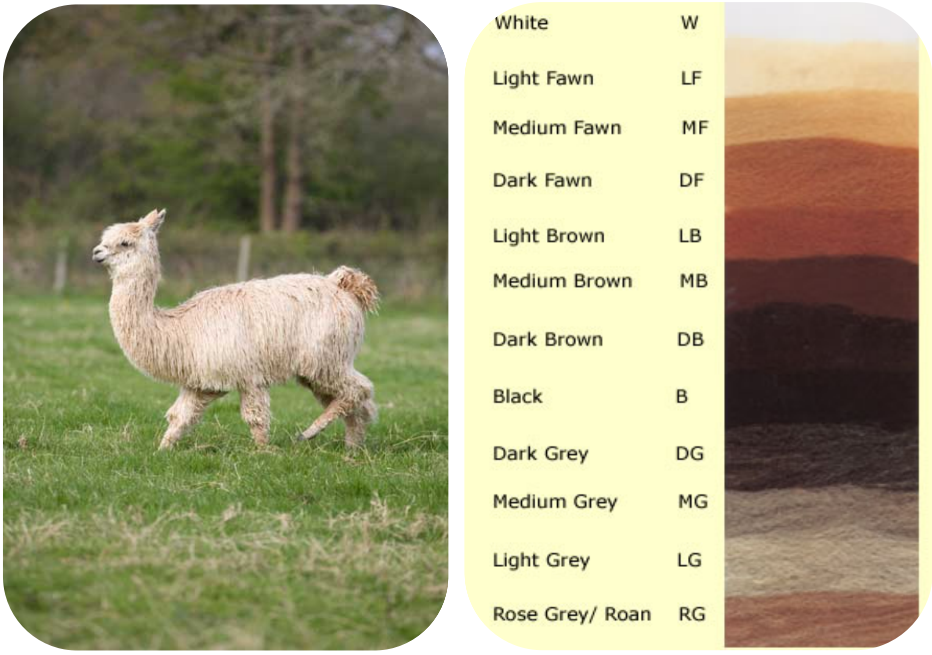


Figure 71 - Alpacas are the most colour diverse, fibre producing animals in the world. There are sixteen official main colours, which can be sub-divided into many more natural shades (Spring Farm Alpacas, 2015).

Figure 72 - Yarn spun from alpaca wool (Wikipedia, 2006)

5.1.2 Biodyes

The increasing of bio-resourced technologies is rapidly transforming the world with their infinite number of applications and possibilities; biotechnological processes play a key role in increasing and promoting sustainable production. Biotechnology practices are, as mentioned, normally associated with sustainable development and green manufacturing processes – waste and pollution control and prevention, resources conservation, cost reduction. Again, the reduction or, rather, the eradication of waste (in every stage of creation) should be part and parcel of quality design, i.e. responsible design able to meet sustainability demands; resources, materials and textile products should not be related with waste. As Braungart & McDonough (2002, p. 104) defend, "to eliminate the concept of waste means to design things - products, packaging, and systems, from the very beginning on the understanding that waste does not exist". This is relevant for this study, as a new method of manufacturing sustainable textile materials and products is being proposed, i.e. safer dyes or clothes produced in a clean manner, representing zero waste and possessing benefits for consumers while guaranteeing business success via varied biology based technologies (either classical or highly sophisticated ones).

The number of projects emerging, embracing biology as a vehicle to design, not only offers a new vision for the development of products (representing a true concept of green, sustainable and, ultimately, safer materials and goods) but, also feed the interest in learning the peculiar aesthetic values of biological resources. Natural ancient dyes, extracted from plants and animals were already mentioned above in chapter 2. Following the biological technologies approach one must, as well, consider the production of coloured compounds through a rather unusual medium – microorganisms.

The huge potential of microorganisms (bacteria, fungi, microalgae, etc.) has been subject of study for a long time in the field of natural sciences, however their application in the creative fields is little unknown. Nonetheless, a growing movement is determined to explore the possibilities of harnessing living systems as an essential and crucial part of creative process in the pursuit for a further sustainable future, as heavily examined and discussed throughout this study.

'Algaemy – crafting our future food' is a project that explores the creative potential of microalgae as pigment in textile printing. "Various species of microalgae are naturally pigmented with blue, green, brown and red tones. These pigments can be extracted using heat and distillation, then turned into natural dyes", Blond & Bieber (2014) stated. Amongst the microalgae organisms used in this project, *Spirulina platensis* and

Haematococcum pluvialis were explored and may deliver a shade of green and orange, respectively, as shown in figure 73. *Spirulina platensis* contains the substance phycocyanin (fig. 74), responsible for the production of a blue-green shade (aqua hue) (Bajaj, 2013), whilst *Haematococcum pluvialis'* orange hue is produced by astaxanthin (fig. 75) (Lorenz, 1999). No further reports are available in regards to the colourfastness properties of these dyes.

Figure 73 - Algaemy (Blond & Bieber, 2014).

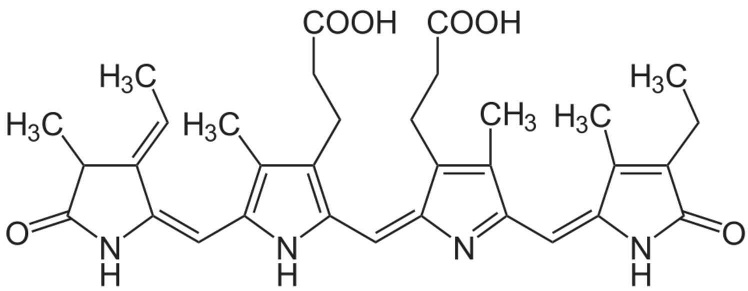


Figure 74 - Phycocyanobilin (Wikipedia, 2008).

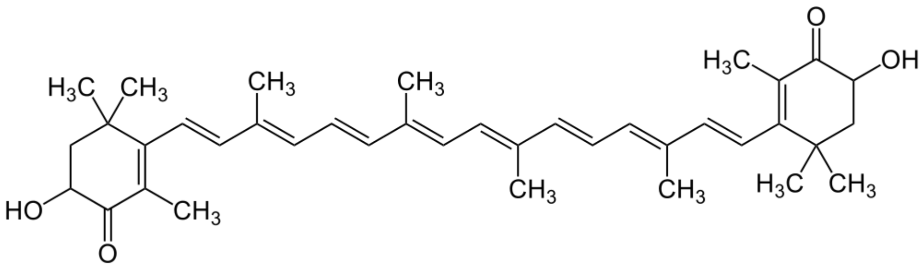


Figure 75 - Astaxanthin Structural Formula (Wikimedia Commons, 2015).

Other studies mention the isolation of a bacterial strain isolated from marine sediments -*Vibrio sp.*-, able to produce large quantities of red dyes (prodiginine), that can be, subsequently, applied onto textiles. Besides the overall great colourfastness dyeing properties, the tested substrates dyed with these microbial prodiginines demonstrated antibacterial activity (Alihosseini, Kou-San, Lango, Hammock, & Sun, 2008). Results on the varied dyed fibres can be observed in figure 76:

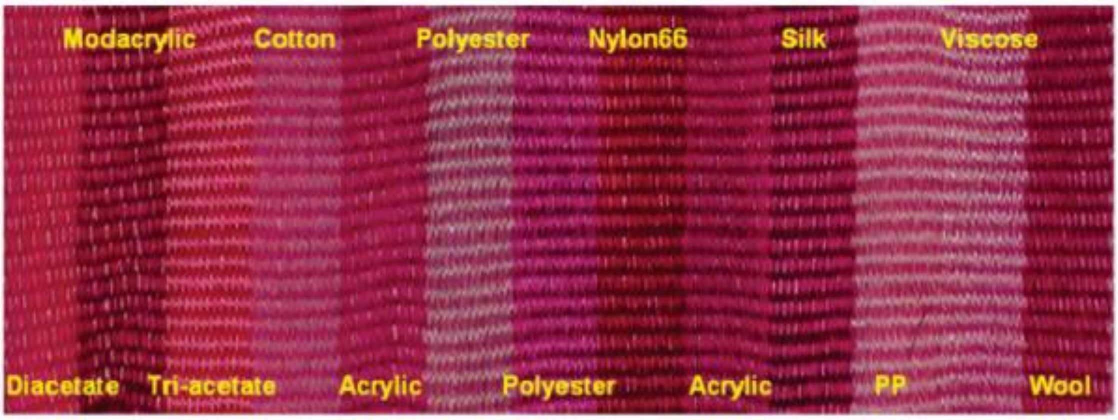


Figure 76 – Varied substrates dyed with prodiginines, from *Vibrio sp.* isolated from marine sediments (Alihosseini, et al., 2008).

Analogous to this probe is the use of bacteria, such as *Chromobacterium* violaceum or *Streptomyces*, to produce natural dyes as mentioned in 2.3.4, table 2 (Santos, 2010). This is a phenomenon that occurs naturally in nature, often found in different plants' microsystems (rhizosphere) (Saravanamuthu, 2010) or glaciers (Lu, et al., 2009), etc. Manipulating at times their environment, different colour shades can be produced (Alive/En Vie, 2013; Chua, 2015). This mechanism of using living bacteria to produce substances might be considered as a sustainable strategy for dyes' mass manufacture, creating less-environmentally damaging materials (Zhao, 2013).

Bacterium such as *Chromobacterium violaceum* along with *Serratia marcescens*, were recently studied to better learn the dyeing properties of bacteria-sourced type of dyes in polyester fibre. Colourfastness properties were tested and evaluated, revealing good washing and crocking fastness but poor lightfastness. This indicates they are suitable for textile dyeing in polyester substrate, usually a very difficult fibre to dye with natural dyes (Wan Ahmad, Ahmad, & Ab Kadir, 2014). The colouring substances depicted in figures 77 and figure 78 are violacein (producing violet/purple) from *Chromobacterium violaceum* and prodigiosin (producing red/pink) from *Serratia marcescens*, respectively.

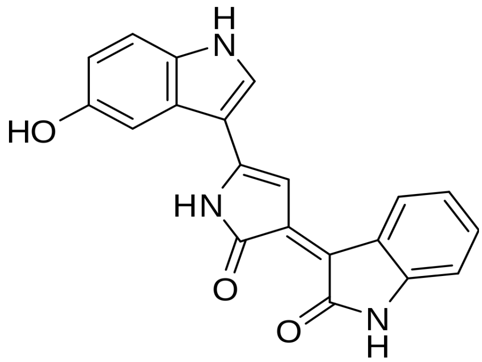


Figure 77 - *Violacein* chemical structure (Wikimedia Commons, 2011).

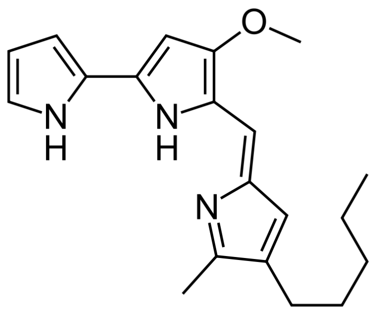


Figure 78 - *Prodigiosin* chemical structure (Wikipedia, 2008).

Streptomyces bacteria may be, similarly, applied to textiles as natural dyes, although more research is needed to better evaluate colourfastness properties and scaling up (Santos, 2010). The next project, Faber Futures (Alive/En Vie, 2013), depicts an experiment prepared with silk fibre as substrate dyed inside a petri dish, recording all the microbial activity during 7 days. The pigments, by-product of the bacteria *Streptomyces*, diffuse through the layers of silk creating staining patterns (fig. 80). The range of hues is provided by manipulating the composition of bacterium nutrition or the environment variables such as incubation temperature, growth period or pH levels (Chua, 2015).

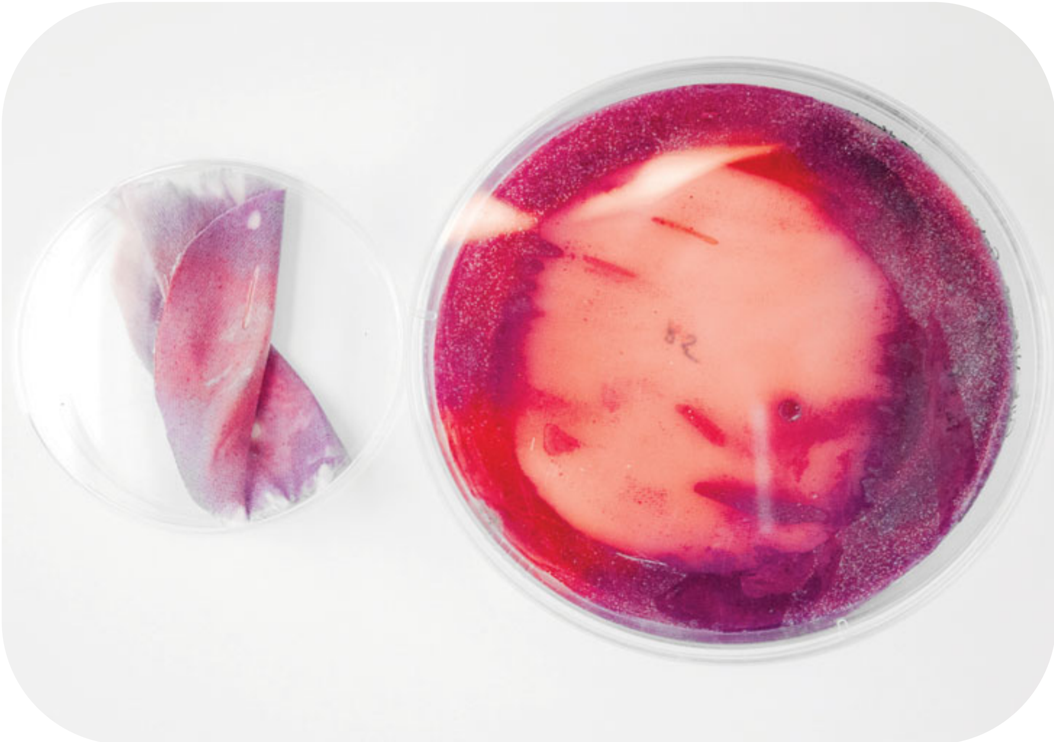


Figure 79 – *Streptomyces* microbial activity diffusing dye through substrate (Chua, 2015).

Figure 80 – Silk scarves dyed via the microbial activity's by-product (Chua, 2015).

Synthetic biology enables the production of specific dyes, as shown in figure 82, holding the potential to meet industry demands, consumer expectations and allow for resilient dyes. Microorganisms can, not only grow rapidly but also, be programmed to provide varied dyes with different properties and different colours, being simultaneously cost effective. However, further deep research on testing colourfastness is required, along with optimised dyeing recipes of application.

Albeit initially engineered for medical purposes (fig. 81 & fig. 82), some experiments reveal bacterium capable of producing varied colorants, ready to be tested as textile dyes. Specific pigments created through these *biomachines* were already isolated in the laboratory.

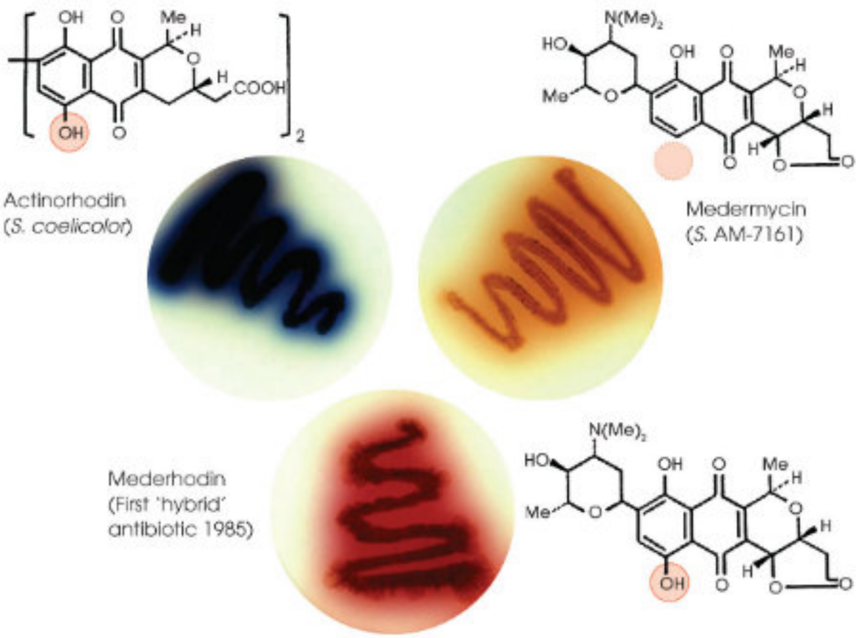


Figure 81 - Using genetic engineer to modify biosynthetic pathways to make new compounds (Hoskisson, 2015).

E-chromi, already mentioned in 4.2, is one of such projects (fig. 82). Born from the collaboration of scientists and designers who engineered bacteria via synthetic biology tools to secrete a variety of coloured pigments, visible to the naked eye.

Standardised sequences of DNA (BioBricks) were designed and inserted into *E.coli* bacteria enabling for the production of chromophores such as red, yellow, green, blue or violet (fig. 84), and allowing, possibly, for their application on textiles (Ginsberg, 2009). The practical part of this study focuses on one of these pigments (*Lycopene*) and evaluates its dyeing properties for the scale up as a textile dye, as examined below in 5.1.2.1 .

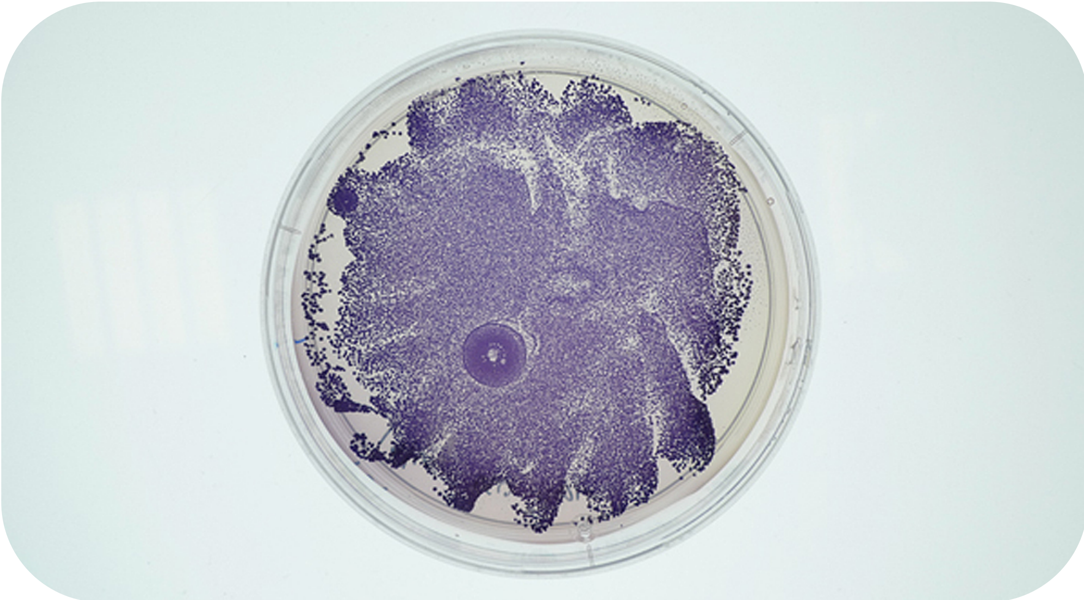


Figure 82 - *E-coli* producing violacein (Ginsberg, 2009).

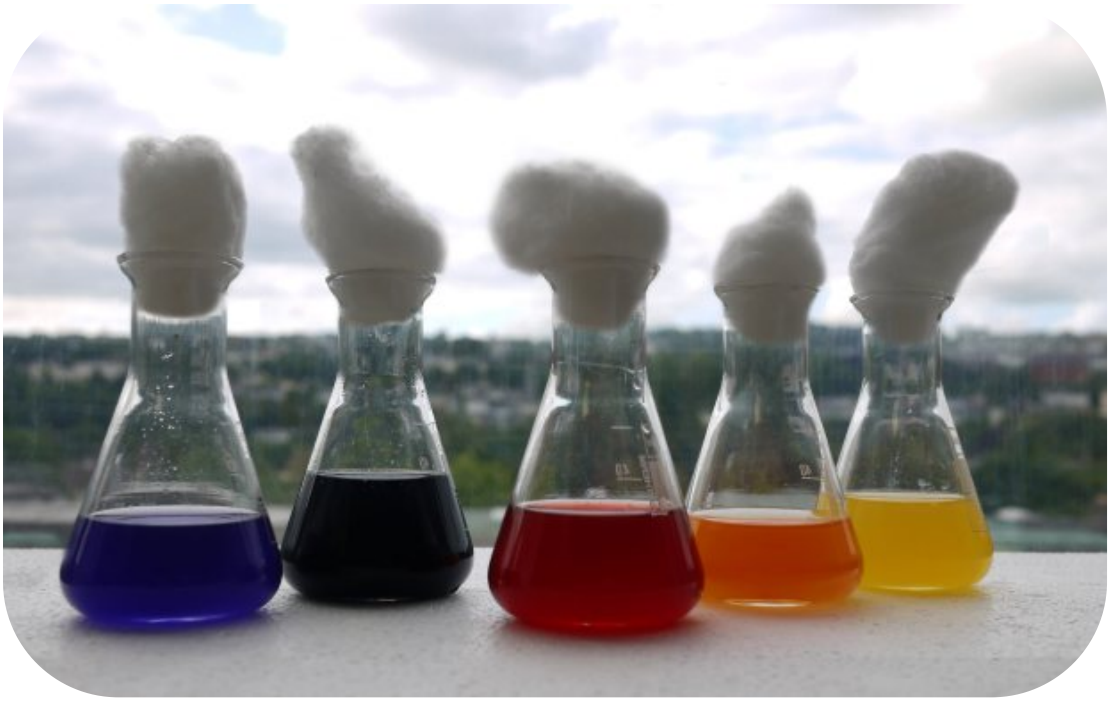


Figure 83 - Erlenmeyer flasks containing genuine pigments from Pili's palette, developed over the Summer at IndieBio EU 2015 (Garvey, 2015).

The rampant growth of synthetic biology endeavours in the past two years includes another project embracing the promising production of bio dyes by microorganisms. Developed in 2015, Pili Bio is a team of young scientist-entrepreneurs in biology, chemistry and design wanting to bring the colours of nature to the everyday life products by implementing bio-based and renewable alternatives, as opposed to the synthetic petroleum-based ones. Pili's dyes are not only made for pens and inks but also textiles. This is a very recent work developed at biotech company IndieBio EU during the summer of 2015 (Garvey, 2015).

5.2 Evaluation of natural dyeing process (experimental study on *Lycopene*)

It is of extreme significance to ponder on resilient systems of manufacturing allowed by the merging of the biological technologies and design creative processes. This dissertation and experimental project focuses on the assessment of biotechnologies that may replace the current methods of production, therefore is relevant to question the scaling up of bio fabrication for the textile and apparel industries.

In an effort to learn and analyse the aspects surrounding the usage of natural/bio dyes in textile dyeing processes, and to evaluate the colouring potential of certain natural substances to be scaled up, experiments were conducted. This experimental study was developed and conducted under supervision in the University of Leeds, School of Design (Leeds, UK), and allows for a deeper understanding of the main issues surrounding the nature of the type of dyeing, biological resources, tools and techniques used, dyeing properties, possibilities, etc.

The practical part of the laboratorial experiments began with getting acquainted with laboratorial techniques related to dyeing. For the first part of the study was critical that both physical and chemical properties of certain dyes and fibres were understood, as their nature usually determines which dyeing techniques are more likely to work (from the dyeing fastness perspective).

We started by studying the physical and chemical dyeing interactions that may happen when different types of textile materials (substrates such as natural fibres like wool or man-made ones like polyester) are dyed with different types of dyeing matter. As explained in chapter 2, the bonding of a certain dye to a substrate and the guaranty of great fastness dyeing properties are very complex processes and sometimes a dye needs to be functionalised in order to be apply with success to a fibre; for this it is vital to learn all the possible physical or chemical exchanges of both materials as well as the understanding of other chemicals, substances or interactions that helps the bonding to form. In sum, it is necessary great knowledge on Chemistry and Physics basic concepts to better establish, control and resolve the different challenges presented by the varied dyeing procedures.

In this first stage many other aspects were also learned – compounds, formulas, solutions, reactions, mixtures, lab utensils, etc. In this phase was also crucial to learn how to work with the different dyeing/washing machines and all the varied different apparatuses and programs as well as the fastness properties assessment tools (*Colour Light Box* or *Grey Scale* measurements), etc. The *Colour Light Box* is used to simulate different light sources to obtain an objective assessment of colour and colour difference, anytime, anywhere; this way, when performing colour contrast evaluations, the assessment error is avoided (as colour appear differently under different lightning sources). The *Grey Scale* is a tool for assessing changes in colour of textiles in fastness tests, e.g. wash fastness, staining fastness. The fastness rating goes step-wise from “note 5 = no change” (best rating) to “note 1 = a large visual change” (worst rating), having as results nine possible values (5, 4-5, 4, 3-4, 3, 2-3, 2, 1-2, 1).

Other critical and challenging part of this stage was to learn all instruments regarding the K/S CIElab system of colour measurement, Spectrocolorimeters and UV-Visible Spectrophotometry techniques; their diverse functions and software programs related to colour analysis. Colour can be described as the perception produced by light reflected or transmitted through objects, so in the strict sense one cannot measure colour but, rather, measure certain factors (e.g. transmittance, reflectance, absorbance) that are responsible for causing this perception of colour. Therefore, for the quantification of colour properties of dyed samples, spectrocolorimeters (K/S Spectraflash SF600 Plus CT Datacolor - model) were used for colour strength and colour depth measurements. Regarding the absorbance, transmittance or reflectance spectra of sample solutions (such as dye bath or exhaustion bath solutions), these were analysed by spectrophotometers (UV Jasco – V 630 - model).

After all this understanding (at the theoretical and practical levels) and necessary training was then decided that experiments to assess the possibilities of using biodyes to dye industrially could begin.

The following figure illustrates colorants expressed by *E-coli* bacteria (via synthetic biology), which operated as a pigment factory. The pigments represent varied coloured compounds – carotenoids (red/orange), melanin (brown), violacein (green/purple) (iGEM Cambridge, 2009).

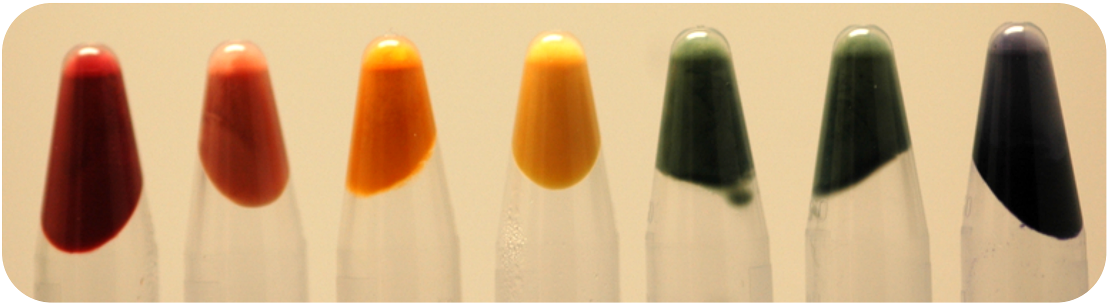


Figure 84 – Rainbown is a set of pigments expressed by modified *E-coli* bacteria by IGEM project, E-chromi, Cambridge. (iGEM Cambridge, 2009).

For this experiment the carotenoid *Lycopene* was investigated. The biochemical pathway of carotenoid synthesis originates two different colour compounds – red Lycopene and orange β-carotene – as shown in the following figure:

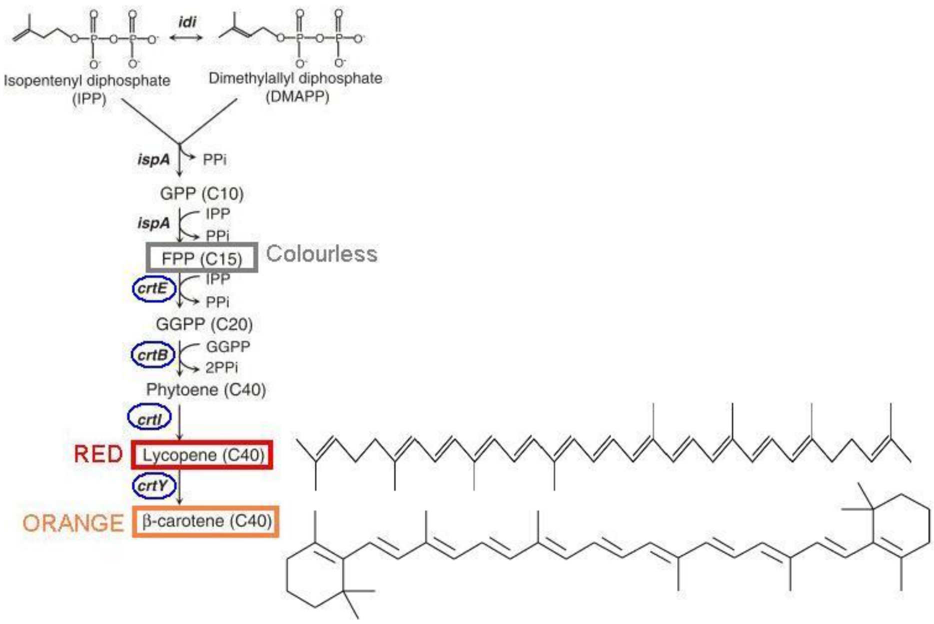


Figure 85 – Biochemical pathway of carotenoid synthesis (iGEM Cambridge, 2009)

Although many studies were conducted on the advantages and properties of natural/biodyes regarding dyeing procedures, colour shades and fastness properties, no information is established on *Lycopene* and its interaction with textiles as a dye. *Lycopene* (fig. 86), extracted from fruits of *Solanum lycopersium* plants (aka tomato), is a known carotenoid pigment representing something around 65% to 98% of its content (Socaciu, 2007). It is found in tomatoes and applied, commonly, as a natural red food colorant and a nutraceutical (Shi, Mazza, & Le Maguer, 2002). Its beneficial and therapeutic properties are well documented and established. It is a powerful antioxidant - the stronger amongst all class of carotenoids - and studies suggest lycopene is effective in varied medical preventive treatments (Watson & Preedy, 2013). Its varied medicinal properties are analysed and documented in many recent studies (Lilic & Misso, 2012; Lee & Foo, 2013; Rao, 2014).

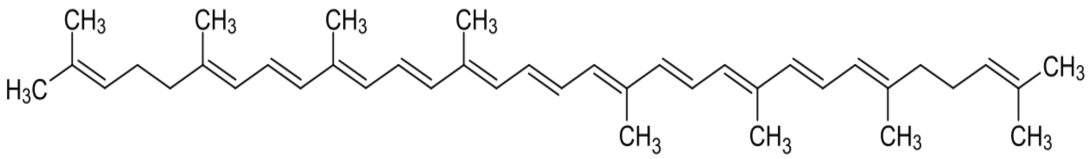


Figure 86 - *Lycopene* chemical structure (Wikimedia Commons, 2009).

Natural fibres were, initially, contemplated as substrates for this study, however, due to the extreme scarcity of knowledge on natural dyes applied to man-made fibres, testing proceeded onto polyester substrate in order to illuminate the interactions occurring if dyed with *Lycopene*.

The experiments between a fibre that can originate from recycled plastic and holds power to be recycled (usually extremely hard to dye with a natural colorant) and a natural dye that can be produce by bacteria, if needed, is a promising step in the field. Firstly, it increases related knowledge on dyeing, chemical and physical proprieties and behaviours between the two materials. Secondly, it provides subject for deeper analysis in terms of sustainability in the sector. Furthermore, aiming to an optimised dyeing recipe makes it further interesting as object of relevant study; achieving a correct tone first time with maximum bonding of chromophores to fibre means less water waste, less dyes and chemicals, less damaging effluents and contamination.

Although mainly resourced from non-renewable petroleum, which extraction has great ecological impact, polyester is believed to be more environmentally friendlier than some natural fibres (Fletcher, 2008; Textiles Environment Design Research, 2014).

Considering the whole lifecycle of polyester, it presents, comparatively, lower energy impacts. It also has the advantage of being recycled, post usage. As a recycled material, it is made from plastic drinking bottles (Polyethylene terephthalate is the raw source of the fibre) that would otherwise be thrown into landfills as stated in TED Research reports (Textiles Environment Design Research, 2014).

For the first time, this project considers the application of *lycopene* chemical substance to textiles. The present study was conducted to explore the colour, wash, light fastness properties of polyester using *lycopene* colorant. Due to the nature (chemical and physical properties) of both fibre and dye, disperse dyeing techniques were used. As mentioned before, some dyes require functionalization so they can be fixed to the substrate and this is the case for our experiment.

Disperse dyeing is a dyeing technique that is usually applied to polyester fibres. Disperse dyeing occurs when the dye is dispersed through hydrolysis and diffused into the fibre assisted by dispersing agents and heating. In our experiment (Appendix I), both materials (*Lycopene* pigment and polyester fibre) do not possess affinity for each other so for the bond to occur different aspects need to be consider; it most important to functionalise the dye. The functionalization happens in different steps described next.

Because of the nature of this dye, the dye bath contains levelling and oxidising agents. The levelling agent is added to the dyeing bath to adjust the dyeing process in order to promote uniform colours; it slows down the dye uptake of the fibres so the dye is taken evenly. The oxidising agent helps prevent the *Lycopene* colorant from decomposing during fixation, encouraging more vibrant colours. The pH adjustment of the water is also of great importance, as it avoids degradation of the dye in case of sensitivity to the hydrolysis process. Here the water is maintained in an acidic level of pH4.5. All these steps are important to facilitate the contact between dye and fibre. During the dyeing process, the *Lycopene* substance needs to be dispersed in water so the hydrolysis occurs, which means that through water the colouring substance is going to break into smaller molecules allowing the dispersion or its distribution to happen. Through the high heating method of application these smaller molecules will penetrate the inside of the polymer fibre that has swollen because of the high temperatures of the dyeing bath. After the fibre cools down it gets back to its normal structure thus allowing the dye to be trapped in its interior.

In sum, dyeing conditions such as the concentrations of the dye, dye bath pH, dyeing temperatures, dyeing times, are utterly important; they were aspects extensively explored as these different variables impact in the uniformity of colour, the dye dispersion and its uptake by the polyester fibre.

Different experiments (each of the many sets had four distinct percentages of dye and different rotation speeds and temperature rising times) followed in order to understand potential dyeing recipes and quality regarding colour depth and shades resulting from the dyeing as well as related fastness properties.

Regarding the investigational method, and in order for the dyeing functionalization to occur, the final experimental dyeing recipe/procedure is as follows (Appendix I):

"*Lycopene* was tested to understand its dyeing properties in Polyester fabric. *Lycopene* dye is a non-water-soluble dye therefore oxidising and levelling agents were used (2g dm^{-3} Ludigol AR + 1g dm^{-3} Levagol DLP) in the dye bath. Polyester fabric was cut into 5g square samples that were dyed with 0.5%, 1%, 2%, 5% *omf* (on the mass of fibre). These samples were dyed at a liquor ratio of 30:1, with the dye bath being maintained at pH value 4.5 (sodium acetate $C_2H_3NaO_2$ and acetic acid $C_2H_4O_2$ solution). The temperature was raised up to 140 ºC and held at this level for 60min. Fabrics were removed and rinsed with water and put to dry at room temperature. Reduction clearing to remove any surface deposited dyestuff followed in a Sodium carbonate (1.5g dm^{-3} Na_2CO_3) and Sodium dithionite (2g dm^{-3} $Na_2S_2O_4$) solution, at a liquor ratio of 20:1, for 15min. at 60ºC."

The different sets of dyeing showed some variation in the hues and uniformity. Some of the hues results are shown in figure 87 depicting the polyester substrate samples dyed with different percentages of *lycopene* dye; when analysing the different graphs shown in figures 88, 89 and 90, from the K/S colour measurements, we can conclude there is four different tones for the orange colour obtained by *lycopene*. The effect of dye concentration was measured and analysed - the more the percentage the stronger the hue. As shown in figures 88, 89 and 90 or in table 6, the K/S values rise with the increase in dye concentration; set of dyeing I presents higher K/S values when compared to sets II and III.

To determine colour uniformity different parameters were applied to the speed rotation and to the temperature rising speed while it is increasing up to 140ºC. Many sets of experiments followed until we concluded that the best results in terms of uniformity of colour were the ones with the parameters shown in table 7. Nevertheless they also present different values between them; by observing the different shades of orange provided and results in table 6, colour intensity is higher at 5% concentration of dye when the dyeing temperature was increased at a slower rate (2ºC/min. up to 60ºC and 4ºC/min. until 140ºC) and rotating at a higher speed (35), with shades differing exponentially in colour, when compared to other parameters (7ºC/min. increasing up to 140ºC at rotation speed of 10 and 20), displaying weaker colour intensities as shown in table 6.

Figure 87 - Polyester samples dyed with different percentages of *Lycopene* colouring substance.

Table 6 - K/S values for Set I, II and III

Samples	Set I		Set II		Set III	
% on mass of fibre	λ Max	K/S	λ Max	K/S	λ Max	K/S
0.5%	460	1.069	460	2.937	460	2.057
1%	460	3.190	460	3.065	460	2.819
2%	460	6.698	460	4.568	460	4.867
5%	460	6.868	460	5.846	460	5.427

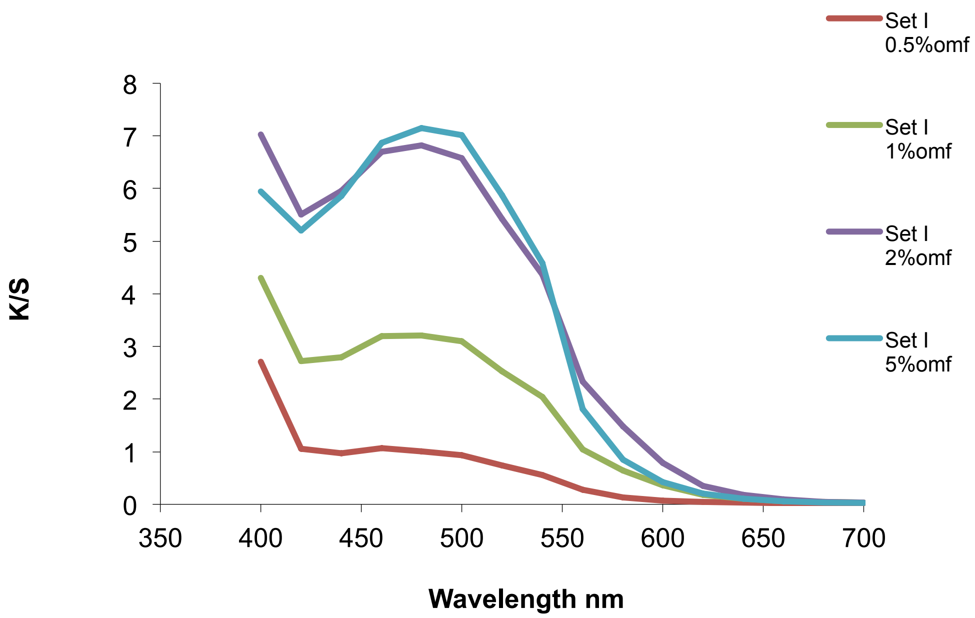


Figure 88 - K/S values of different percentages of *on the mass of fibre*; set of dyeing I.

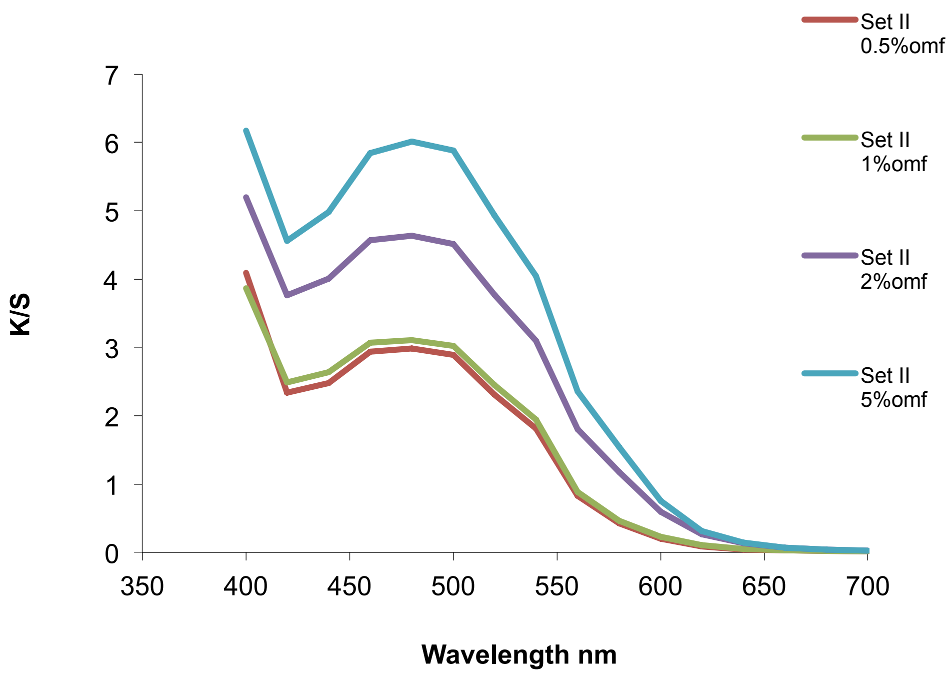


Figure 89 - K/S values of different percentages of *on the mass of fibre*; set of dyeing II.

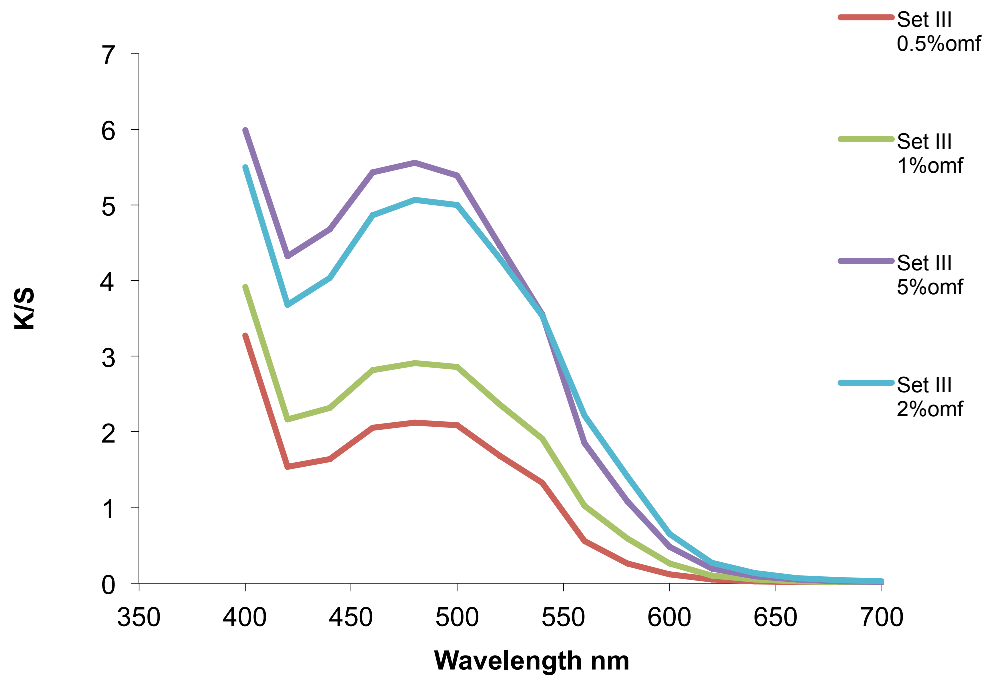


Figure 90 - K/S values of different percentages of *on the mass of fibre*; set of dyeing III.

Table 7 – Dyeing parameters

Samples	Dyeing temperature	Dyeing speed rotation
Set I	2ºC/min. up to 60ºC - 4ºC/min. up to 140ºC	35
Set II	7ºC/min. up to 140ºC	20
Set III	7ºC/min. up to 140ºC	10

As illustrated in figure 91, contemplating the different exhaustion dye bath samples (wastewater solutions), it is evident that the higher the percentage of *lycopene* dye, the bigger the loss of it to the water, i.e. the dye uptake is higher in the sample corresponding to the applied 0.5% of dye on the mass of fibre (sample 4, far right). The percentage of dye that did not bond to the fibre is higher in sample 1 (corresponding to 5% *omf*) as highly observable in the image (figure 91). This is also analysed in the results for the absorbance spectra of dye bath and wastewater solutions (UV spectrophotometric analysis to the dyeing and exhaustion baths) as shown in table 8 or in the graphs in figure 92.

Table 8 - UV-Visible spectrophotometer values for dyeing set I

Samples	Set I – Dye bath		Set I – After wash	
% on mass of fibre	λ Max	K/S	λ Max	K/S
0.5%	470	0.344	470	0.042
1%	470	0.683	470	0.058
2%	470	3.675	470	3.612
5%	470	3.951	470	3.882

This means that, in this specific case, to achieve a stable colour and less waste in the effluents, 0.5% of the dye on the mass of fibre is sufficient to impart colour to the polyester sample, the remaining will be lost. Nevertheless lycopene is a natural dye so it does not represent hazard to the ecosystems as it possesses high affinity with nature being biodegradable.

Figure 91 - Samples of exhaustion dye bath; 5% o.m.f., 2% o.m.f., 1% o.m.f., 0.5% o.m.f. (from left to right).

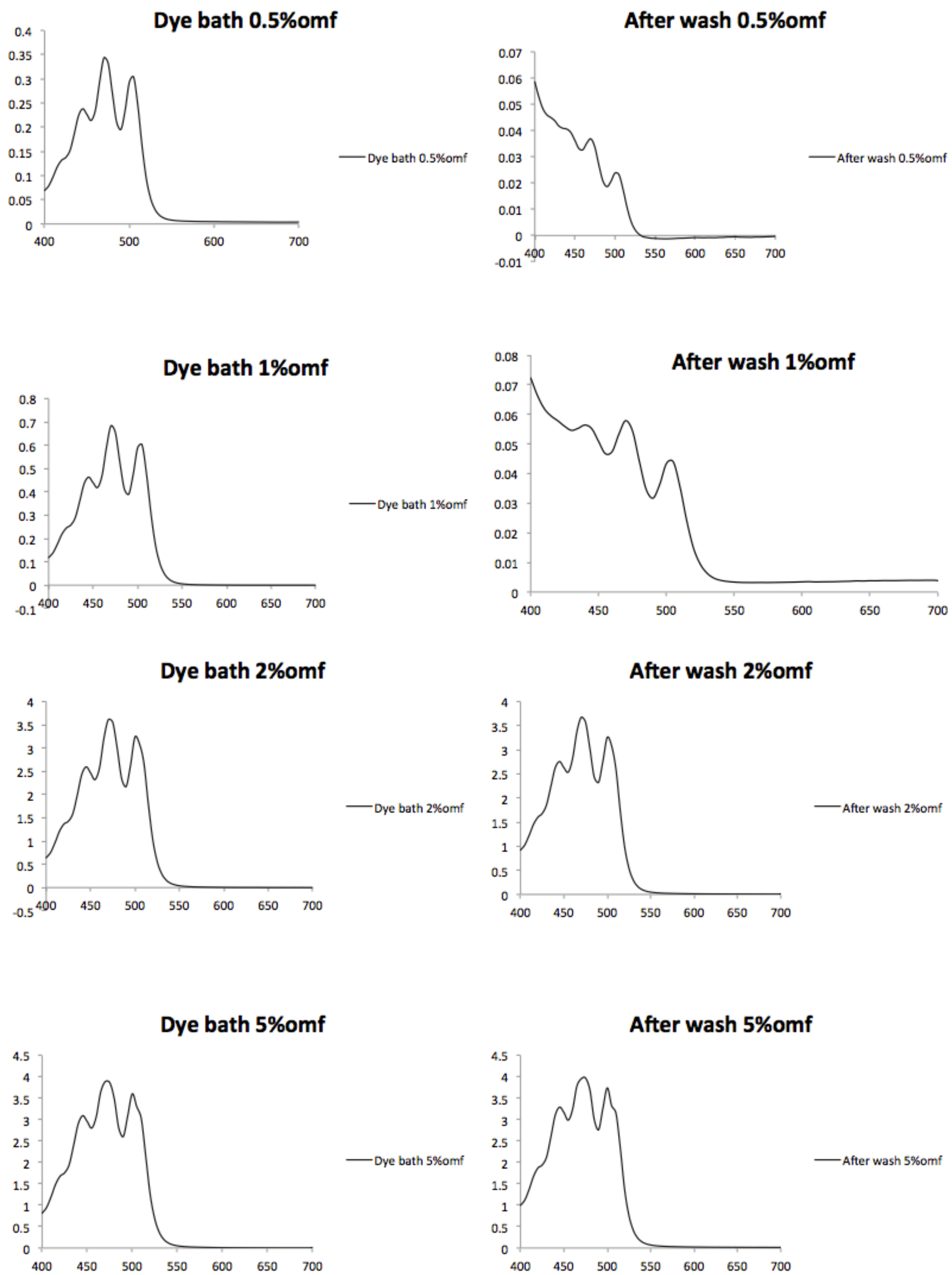


Figure 92 - The absorbance spectra of dye bath and exhaustion bath solutions (set I).

Overall fastness properties were also investigated, exploring different variables. Concerning the light fastness property, which was also observed, little fading was noticed. In regards to the eventual dye leaching and potential staining, the washing aspect was investigated; when observing the multifibre test strip in figure 89, no dye molecules were transferred to any other type of fibre. This is utterly important as it reveals that during the washing of clothes no colour bleeding occurs between items in the load. This was determined by carrying out washing tests, using a specimen of dyed fabric in contact with a (not-dyed) multifibre strip, inserted into tubes containing a solution of reference detergent and water. These tubes were agitated (washed in a rotating mechanical action) for 30 min. at 40º C temperature. The change in colour of the specimen and the staining of the adjacent fibres were assessed with the reference of the original fabric sample, using standard *Grey Scale* measurement tools (results in table 7).

Figure 93 – An example of one of the dyeing samples and its washfastness testing results. Washfastness results are visible to the far right, on the white multifibre ribbon, showing no colour-bleeding occurrence during the specimen washing.

Overall, the dye testing results show that the natural lycopene dye, able to be manufactured by microorganisms (if needed), provides for a suitable and viable natural/bio textile dye and, most importantly, in an ecological way. The procedures (dyeing process) were developed in order to guarantee an optimised recipe by improving the dyeing process as explained above (contemplating, exploring and analysing the distinct variables). An optimum recipe, as normally termed, is the dyeing procedure in which the goal is to use the minimum dyes (or percentage of the dye) and chemicals as possible, still guaranteeing, the performance of the colouring compound, i.e. getting a correct tone first time with maximum fixation. This means less water waste, less dyes and chemicals, less damaging effluents and contamination.

Table 9 - Colourfastness of samples investigated

Samples % omf	Washing fastness	Staining of wool	Staining of acrylic	Staining of polyester	Staining of polyamide	Staining of cotton	Staining of diacetate
Set I-0.5%	4/5	5	5	5	5	5	5
Set I-1%	4	5	5	5	5	5	5
Set I-2%	4	5	5	5	5	5	5
Set I-5%	4	5	5	5	5	5	5
Set II-0.5%	4/5	5	5	5	5	5	5
Set II-1%	4	5	5	5	5	5	5
Set II-2%	4	5	5	5	5	5	5
Set II-5%	3	5	5	5	5	5	5
Set III-0.5%	4/5	5	5	5	5	5	5
Set III-1%	4	5	5	5	5	5	5
Set III-2%	4	5	5	5	5	5	5
Set III-5%	3	5	5	5	5	5	5

As demonstrated throughout the laboratorial experiments and subsequent results we can conclude that *lycopene* as a dye offers good colourfastness properties and with little ecological impact. Furthermore, it delivers an orange colour, possessing a somewhat natural feeling, visually, which might be particularly attractive to designers. This study proves, simultaneously, that research is crucial and highly in demand given the scarcity of recipes (i.e. biological resources, dyeing potential of unknown biodiversity, optimum recipes, behaviour between fibre and natural dyes, optimised dyeing processes, etc.) on natural dyeing for industrial purposes. Additionally this practical study validates that the substance *lycopene* can be applied as a textile dye to impart colour to a polyester fibre, a substrate that is proven difficult to dye, especially with a natural dyestuff and may be easily scaled up.

6. Conclusion

6.1 Final considerations

Textiles and apparel industries' negative impacts on the entire ecosystem are varied: spinning, weaving and industrial production is associated with non-renewable energy and waste. Sustainability issues directly affecting the sector are numerous and, in contrast, the strategies to overcome the problems are scarce. This is particularly true and matter of great concern in developing countries such as China and India. Finishing processes, such as dyeing, consume large quantities of water and harmful chemicals, usually released into the atmosphere. Whilst all the waste and the numerous volatile agents found in textile effluents represent a threat to all ecosystems, finding viable solutions that boost valid sustainable processes within the textile industry is a massive challenging task. Major sustainability problems are not easily resolved with just a few adjustments. The need to reform old systems, current practices and the inclusion of sustainable drivers at the core of creative process makes it necessary to explore key contextual issues. Options are discussed along this study, by questioning, analysing and proposing new design concepts able to fully engage with the multifaceted challenges of this new century.

As shown in this dissertation, many studies indicate that transformations need to be radical and shaped according to three distinct principles – respect for nature, social equality and strategic business/economic planning (provided it comprises the first two).

The dyeing industry is particularly challenging when exploring potential, feasible, and effective sustainability strategies. Colour is an essential element of the textile and apparel world, one of the most powerful and established sectors on the planet and, naturally, reluctant to changes. Processes did not change much since the Industrial Revolution.

The dyeing procedure is, on the other hand, chemically, a rather complex practice, involving critical expertise so the colours are fixed to the fibres. Colourfastness and uniformity are utterly important aspects to consider in a dyeing procedure, as the eventual colour fading and bleeding are to be avoided. The permanent bond of the dye and the substrate is essential, especially when analysing the dictum *reduce, reuse, recycle* i.e. the more stable and long-lasting the colour, the better.

Along with the aforementioned reasons, the dyeing problematic includes the lack of safety of materials in use; besides the effluents and the risk for the environment due to contamination, wearing colours is a daily threat for consumers (and those working with the material), as they carry severe risks associated the length of time of exposure to it, oral ingestion, skin and respiratory tract susceptibility.

In contrast, the trendy alternative adopted by many *slow fashion* brands of using natural ancient dyes as a substitute to synthetic ones is a healthier choice, due to their biodegradable and less toxic nature or medicinal properties. However, their usage alone is, most of the time, not enough to resolve, at 100% level, the sustainability issues. When assessing their characteristics, textiles dyes, both synthetic and natural, have many advantages and disadvantages, as shown in figure 90.

The most significant beneficial features of natural dyes application is, besides the ecological aspects, their medicinal properties (e.g. antibacterial, antimicrobial), meaning that fabrics dyed with natural dyeing material offer plausible and safer clothes, particularly to groups that are more susceptible, such as babies, children and the elderly.

Added advantage of natural dyestuff application is the possibility of being an approach, or rather, a justification to protect biodiversity (since we would depend on its existence for the understanding and the creation of natural colouring compounds or substances of interest). The biodiversity preservation subject is of crucial importance and is directly intertwined with some of the less pleasant aspects of natural dyeing, which is the lack of knowledge, firstly, regarding to the dyeing potential of most of the biological resources in the planet and, secondly, their application recipes. Some data containing relevant information on dyeing procedures was lost and most knowledge on the behaviour or interaction of natural dyes (or potential natural dyeing substances to be discovered) with the varied fibres were never investigated. This is one of the reasons why further research is absolutely vital in this field.

This aspect also guided this project in terms of choice of material, when conducting laboratorial experiments and justifies, on the other hand, the practical stage of this research, discussed in chapter 5.

One of the most negative facets of natural dyes is their cost. These are expensive substances due to their difficult and lengthy methods of extraction, production and application (as observed in 2.3.3), which in turn have great impact in the quantity supply; their limited quantity makes them extremely problematic to scale up. It was previously mentioned, in chapter 2, innovative ultrasound techniques that can greatly improve the extraction and the application (fixing techniques improving colourfastness properties) procedures involving natural dyes.

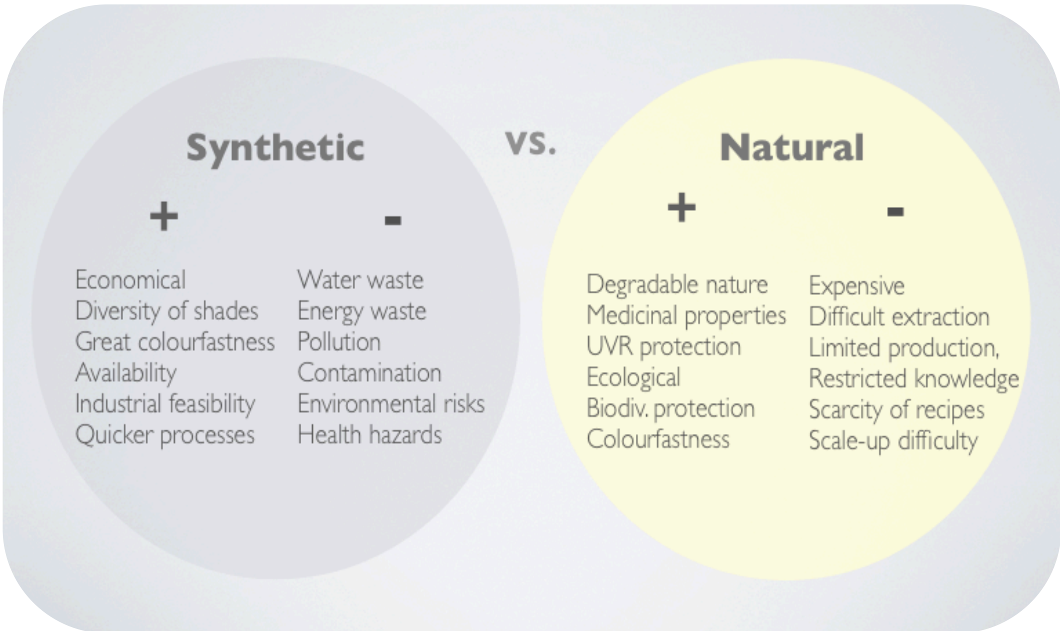


Figure 94 – Synthetic dyes versus natural dyes concerning advantages and disadvantages, in regards to their application in the textile dyeing industry.

We feel obliged to stress, at this point, that regarding the extraction process (and taking into account we defend and propose biotechnology as a potential alternative to the current production processes), when these natural substances are produced via microorganisms (as a living machine) the extraction issues (difficult and lengthy procedures) revolving around the natural dyeing process no longer exist. Furthermore, their fast growth and practicability make them promising to tackle the sustainability issues, especially in regards to their cost, which would then inevitably drop. The availability, and the speed at which the natural substances can be produced, is impressively increased, meaning that the textile industry can meet their industrial requirements in terms of quantity. On the other hand, if microorganisms/living organisms are engineered to produce dyes via synthetic biology (dyes that would otherwise be originated by animals or plants) we could simply eliminate unsustainable monocultures (specifically created to extract dyes) or even reduce the destruction of biodiversity in order to get products.

The water waste is still a problem when dyeing with natural dyes, however, as briefly mentioned in 2.3.2, waterless dyeing sophisticated technologies are slowly being implemented. These new techniques of dye application are extremely important as they reduce massively the industrial dyeing environmental footprint by decreasing the level of wastewater and the residues thrown to the atmosphere as well as the fossil fuel generated energy.

Concerning the colour shades provided by natural dyes, as examined in 2.3.3, where we survey some of the natural ancient dyes, we can conclude that the three primary colours (magenta, yellow, cyan) are well represented. Besides the red, yellow and blue shades, many other colours and hues may be obtained with the addition of varied mordents. Many more tones may follow through either further enhanced new dyeing techniques or accomplishing deeper knowledge in the subject of biological resources with potential dyeing properties.

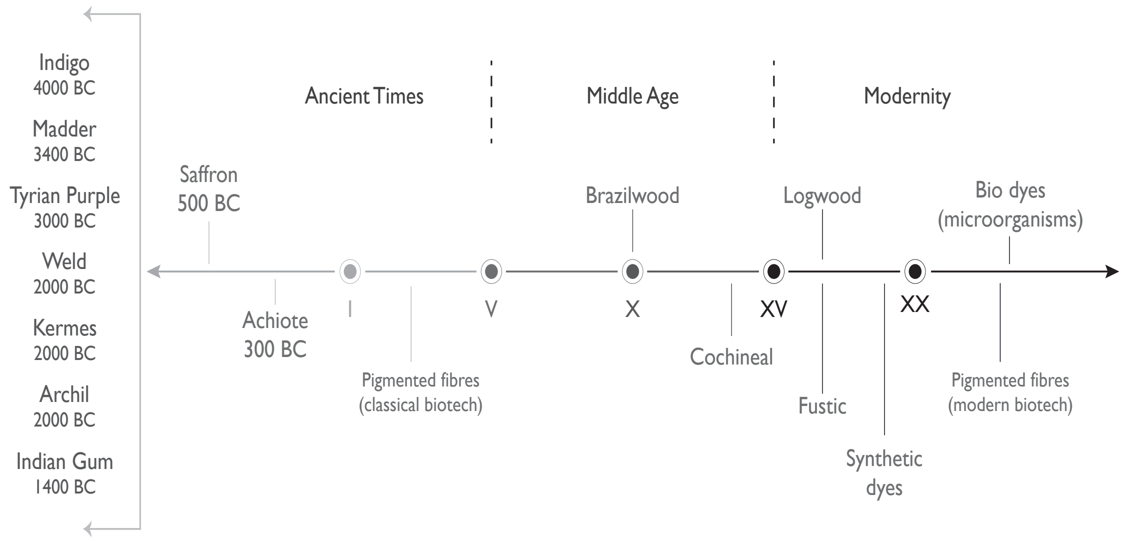
The other alternatives to reduce the textile and dyeing industry ecological footprint are discussed in 5.1.1, where there is the mention to fibres that are naturally pigmented (coloured fibres occurring naturally in nature, not man-manipulated) and the coloured fibres originated from genetically modified organisms, which open, improve and increase the possibility of eliminating all dyeing processes.

Concluding, sustainable dyeing alternatives involve deeper knowledge on bio resources with dyeing potential and techniques of extraction, production and application as well as sophisticated green technologies of producing natural colouring compounds through bacteria.

So that the Excellency in textile product design may be attained, different and innovative technologies need to be explored and included in the creative process, especially when contemplating the lifecycle of whatever goods are produced. We consider science plays a significant role in the sustainable creation of goods, as argued in this dissertation, in particular, the appropriation of technologies with a biology-based approach; we trust they are unexplored, notably in the textile design field, and are of great potential to help accomplish an effective sustainable improvement within the textile sector and the design field. We go further in stating that a biological revolution as began and the way we designed or manufactured things until the present day is closer to obsolete.

Regarding dyeing processes and evolution, we propose the following speculative table, along with the suggested sophisticated technologies, clever design of textile products and values attached to them.

Table 10 – A speculative timeline on the evolution of the textile dyeing process



In the past recent years, technologies using biological resources have played (and continue to play) a massive role in varied different industries, fighting sustainability issues and improving lifestyle in general; this is no exception for the textile and apparel industry. Biotechnology is believed, as stated, to be a channel to help enhancing wellbeing, to assist social innovation, to promote the protection of nature by reducing its depletion, and finally to provide, in the long run, for a sustainable economy.

Figure 95 – Sustainability and the responsible design landscape (Appendix B).

As discussed, it is most important that products emerge around us embracing values of universal equality and respect by tackling the main issues interrelated to their concept, existence, evolution and expiry, i.e. the way we plan them, the way they are manufactured, what values can they provide, their benefits while in use, how they are able to assist or enhance our lifestyle, how and what do they become when eventually ceasing to fulfil their primary objective, etc. Biology-based technologies, either classical or sophisticated, provide, as discussed, for highly innovative ways to create fashion and textile materials or products that are sustainable i.e. they are focused and designed to be capable of dealing with core industrial issues regarding the sustainable development of garments and dyes, offering alternatives that allow for enhancing the performance of materials and products. Furthermore, they represent a fresh perspective where the use of bioresources is grasped as biological machine. As indicated along this dissertation, these natural processes may even replace industrial or mechanical systems in the near future.

Closing, although the multiple applications of biotechnology and its enormous potential to overcome the challenges faced by contemporary society, its evolution to surgical bio techniques is occasionally regarded as radical as it is innovative. The strategies involved with this kind of technology offer truly visionary concepts of bio-fabrication, bioremediation, life improvement and sustainability in general; they do provide for a reduction of the ecological burden of the current industrial processes, in particularly, that of the dyeing sector. However, when analysing the significant advances that took place in the past years, with genetic engineering and avant-garde synthetic biology, a broad-spectrum of ethical concerns emerge. With their infinite possibilities the questions of moral nature are, simultaneously, likely to arise.

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8. Appendices

Appendix A. Global Communities, Biotechnology and Sustainable Design – Natural / Bio Dyes in Textiles

6th International Conference on Applied Human Factors and Ergonomics (AHFE 2015) and the Affiliated Conferences, AHFE 2015

Global Communities, Biotechnology and Sustainable Design – Natural / Bio Dyes in Textiles

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Abstract

Never before apparel industry has lived such a fast pace period. Brands, collections, colours and styles are increasingly being created every season, changing accordingly to the many trends society generates. People and lifestyle transforms rapidly, and so their expectations. With all the demanding adjustments this sector has to currently face, it seems, though, the concept of clothing remains the same for the past centuries; textiles are still attached to old ways of thinking materials and dated methods of production and application revealing reluctance to dramatic changes and radical innovation within the sector.

Sustainable materials integrating technologies, environment, communities, people, language and culture that will inevitably emerge as products are still seen as a challenge[1]. Textiles' world is vast and varied with many raw materials and techniques employed. It is one of the most pollutants sectors, contributing a great deal to the environmental impact, poor working conditions, energy and water waste, contamination, etc. It is crucial the focus on how to reduce the textile production environmental footprint and the consideration on how materials can allow for a more sustainable future, whilst, simultaneously, promoting and enhancing wellbeing and influencing lifestyle[2].

Consumers are increasingly aware of textiles industry's hazards and demand for quality products, planned accordingly to their function, lifecycle and produced within eco-friendlier methods. The apparel industry is more than style and excitement; consumers expect colour and change allied to quality and function. Not only are they attentive to material's quality, provenience, production processes and the friendliness of these methods but they also question their function, how these products change over time accordingly to people's lifestyle, adapting to expected changes as one travels, ages, transforms, experiences, cease to consume, etc.

Sustainable strategies to reduce environmental impact find in biotechnology an infinite number of applications and it has been widely used since a few decades, mainly dealing with clean technologies3. The use of bio resources as a technology is millenary but as a

scientific subject it took only the usage of new tools to discover different uses and functions of plants, animals, or microorganisms thus allowing for the improvement of this new field of human knowledge4.

Biotechnology was always applied, since ancient times, in textiles, from fibres production, dyes management or residual waste. From classic to modern biotechnology, its evolution takes place through significant advances in genetic engineering and synthetic biology where the use of living organisms is seen as a biological process that may replace industrial or mechanical systems. Sometimes introducing visionary and radical strategies for improving the performance of objects around, its multiple applications are focused and designed to deal with sustainable development of materials and core industrial issues5.

Sustainable design seeks innovation within the sector. Science is being introduced as a methodology in the creative process that slowly embraces different technologies, social improvement, environment and wellbeing, while projecting products.

Textiles and fashion industry's negative impacts on the entire ecosystem are varied: spinning, weaving and industrial production is associated with non renewable energy and waste; finishing processes, as dyeing and printing, consume vast amounts of water and chemicals, releasing numerous volatile agents into the environment6. Dyeing has always been, throughout the centuries, one of the most important industries with a remarkable evolution. Colour was always of a major importance for mankind, playing crucial roles in both the social and economical contexts. Related to different aspects of human behaviour, symbolism and aesthetics, colour is known to influence people in many levels such as emotional7 or shape perception8; it is known to influence hormones, blood pressure and body temperature9.

As an influence agent, it is particularly crucial to the commercial success of fashion and textile products. Besides print and pattern, consumers demand for basic characteristics in textiles. These must resist to the agents that cause colours to fade (washing, light, perspiration, etc.). To guarantee these properties, dyes conferring colour to fibres must present high-affinity properties with the latter, allowing for a greater colour fastness and uniformity. They must, simultaneously, allow for a great range of colour shades and be cost effective. The high number of synthetic dyes is justified given the requirements of industry and consumers. However, most of synthetics dyes or dyeing methods are regarded as little sustainable partly due to effluents associated to these finishing processes, which, if not conveniently treated, can be harmful to the environment and human health10,11,12,13.

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Keywords: Sustainable Design; Textile Biotechnology; Dyeing technology; Natural Dyes; Bio Dyes

Introduction

1.1 Sustainability in textiles products

Colour has always been important in the social and economical context of mankind. It is one of the most important aspects of fashion and textiles, with a long history and remarkable evolution. Dyeing process effectiveness is, therefore, crucial to the textile industry success, attentive on how colours influence consumers. Nevertheless, dyeing methods are often associated with water waste, fossil fuel generated energy, toxicity and contamination, posing a serious threat to the environment and human health. Certain synthetic coloured substances are regarded as toxic and pollutant leading consumers to question textile products' sustainability. The search for natural coloured substances is increasingly intensifying, as these are perceived as being compatible to nature and less toxic to consumers and the ecosystem. Sophisticated technologies such synthetic biology plays a crucial role in the development of dyes capable of meeting consumer's demands as well as this new century's requirements. In this study we explore the dyeing properties of a class of carotenoid - Lycopene - usually used in the food industry as a red colorant that has been recently synthesised through bacteria. The colouring ability of Lycopene dye has been tested on polyester substrate and found to be suitable for textile dyeing.

1.2 Sustainable materials: dyes

Consumer's expectations and inevitable issues related to sustainability within this industry such as energy waste, contamination, climate, environment and lifecycle of a product have triggered a preference for organic materials. This has also led to the gradual interest and reintroduction of natural dyes (generally used in ancient times, mostly derived from plants) in the market. These bioresourced dyespossess a biodegradable nature and are, generally, considered safer. They possess a higher level of affinity with the environment causing less impact. Depending on the natural dye, some are known to possess great colourfastness properties (applied with or without mordents), fair range of colours, protection properties against UVR8 as well as medical properties as antimicrobial9,10 and anti-inflammatory advantages11.

Despite the vast array of coloured compounds found in nature, only a small parcel of it is applied to textiles. An extensive amount of data got lost at the time of the introduction of synthetic dyes in the market and most knowledge on resources, extraction techniques and applying methods is limited. Deeper understanding on materials - dyes and fibres – and the biodiversity yet to be explored is required. Dyeing with natural dyes tends to be, simultaneously, expensive due to their rather complex processes of extraction and application and the very limited amount of dyestuff provided. Knowledge on bio sources, and their different properties, is vital to push boundaries on applicable research within the sector.

Technologies using bio resources are not new but their evolution is rapidly transforming the world with their infinite number of possibilities. Furthermore, the scope of science allows, currently, for a completely new radical way of rethink materials that will emerge as products around us.

Regarding dyes, state of the art technologies consist in the production of coloured compounds by microorganisms. Dyes produced by this type of biosources are created through a mechanism that uses living bacteria, often found in different plants' microsystems (rhizosphere), manipulating at times their environment. This living machine might be considered as a sustainable design strategy for mass manufacture. Its effectiveness finds in synthetic biology a way to enable the production of specific dyes designed to meet the industry's demands and consumer's expectation. Microorganisms can, not only grow fast but also, be programmed to provide varied dyes with different properties and different colours, being simultaneously cost effective.

Some pigments created through bio machines were already isolated in lab. "E-chromi" is one of such projects, born from the collaboration of scientists and designers who genetically engineered bacteria to secrete a variety of coloured pigments, visible to the naked eye. Standardised sequences of DNA (biobricks) were designed and inserted into E. coli bacteria enabling for the production of colours such as red, yellow, green, blue or violet, possibly allowing for its application on textiles. One of the isolated pigments is Lycopene, a red shade compound found in tomato fruit. To understand if this type of dye can be scaled up for industry, experiments onto different substrates must be conducted.

Lycopene (Figure 1), extracted from fruits of Solanum lycopersium plants, is a known carotenoid pigment representing something around 65% to 98% of its content12. It is found in tomatoes and applied, commonly, as a natural red food colorant and a nutraceutical13. Its beneficial and therapeutic properties are well documented and established. It is a powerful antioxidant - the stronger amongst all class of carotenoids – and studies suggest Lycopene is effective in varied medical preventive treatments14. Its varied medicinal properties are analysed and documented in many recent studies15,16,17,18.

Although many studies were conducted on the advantages and properties of natural dyes regarding dyeing procedures, colour shades and fastness properties, no information is found on Lycopene and its interaction with textiles. For the first time, this project considers the application of Lycopene dye to textiles. We conducted the present study to investigate the dyeing and fastness properties of polyester using Lycopene pigment. Dyeing conditions such as the concentration of the dye, dye bath pH, dyeing temperature, dyeing time and the overall fastness properties were investigated.

Nomenclature

K/S colour strength

wavelength (nm)

UVR ultra violet radiation

2.1 Materials

2.1.1 Dye material

Lycopene natural food colorant, obtained from LYCORED COLORS (Fig. 1).

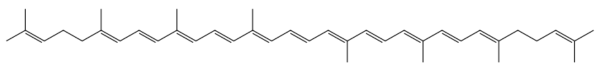

Fig.1. Chemical structure of Lycopene

2.1.2 Fabric

Polyester fabric (Polyester Sateen Glacier White) was obtained from Whaleys (Bradford) LTD. Harris Court, Great Horton, Bradford, West Yorkshire, BD7 4EQ England.

2.2 Method

2.2.1 Dyeing procedure

Lycopene was tested to understand its dyeing properties in Polyester fabric. Lycopene dye is a non-water-soluble dye therefore oxidising and levelling agents were used (2g dm-3 Ludigol AR + 1g dm-3 Levagol DLP) in the dye bath.

Fabric was cut into 5g square samples that were dyed with 0.5%, 1%, 2%, 5% omf. These samples were dyed at a liquor ratio of 30:1, with the dye bath being maintained at pH value 4.5 (sodium acetate $C2H3NaO2$ and acetic acid $C2H4O2$ solution). The temperature was raised up to 140 ^{o}C and held at this level for 60min. Fabrics were removed and rinsed with water and put to dry at room temperature. Reduction clearing to remove any surface deposited dyestuff followed in a Sodium carbonate (1.5g dm-3 $Na2CO3$) and Sodium dithionite (2g dm-3 $Na2S2O4$) solution, at a liquor ratio of 20:1, for 15min. at 60^{o}C.

Other sets of samples followed in order to understand their quality regarding colour depth and shades of the dyeing. To determine colour uniformity different parameters were applied to the speed rotation and to the temperature rising speed while increasing up to 140^{o}C as shown in Table 1.

Table 1

Dyeing parameters

Samples	Dyeing temperature	Dyeing speed rotation
Set I	2°C/min. up to 60°C - 4°C/min. up to 140°C	35
Set II	7°C/min. up to 140°C	20
Set III	7°C/min. up to 140°C	10

Results and Discussion

3.1 Effect of dye concentration

Experiments were carried out to find the effect of the amount of dye used onto the polyester fibre. As shown in Figures 2, 3, and 4, the K/S values rise with the increase in dye concentration. Set of dyeing I presents higher K/S values when compared to sets II and III.

3.2 Effect of speed rotation and temperature

The experiments carried out onto polyester substrate show the potentiality of Lycopene application as a natural textile dye. By observing the different shades of orange provided and results in table 1, colour intensity is higher at 5% concentration of dye when the dyeing temperature was increased at a slower rate (2°C/min. up to 60°C and 4°C/min. until 140°C) and rotating at a higher speed (35), with shades differing exponentially in colour, when compared to other parameters (7°C/min. increasing up to 140°C at rotation speed of 10 and 20), displaying weaker colour intensities as shown in Table 2, and after light exposure in Table 3.

Table 2

K/S values.

Samples	Set I		Set II		Set III	
% on mass of fibre	Max	K/S	Max	K/S	Max	K/S
0.5%	460	1.069	460	2.937	460	2.057
1%	460	3.190	460	3.065	460	2.819
2%	460	6.698	460	4.568	460	4.867
5%	460	6.868	460	5.846	460	5.427

Table 3

K/S values after light exposure.

Samples	Set I		Set II		Set III	
% on mass of fibre	Max	K/S	Max	K/S	Max	K/S
0.5%	460	1.024	460	2.259	460	1.748
1%	460	3.067	460	2.077	460	2.068
2%	460	3.896	460	2.562	460	2.873
5%	460	6.323	460	2.991	460	3.507

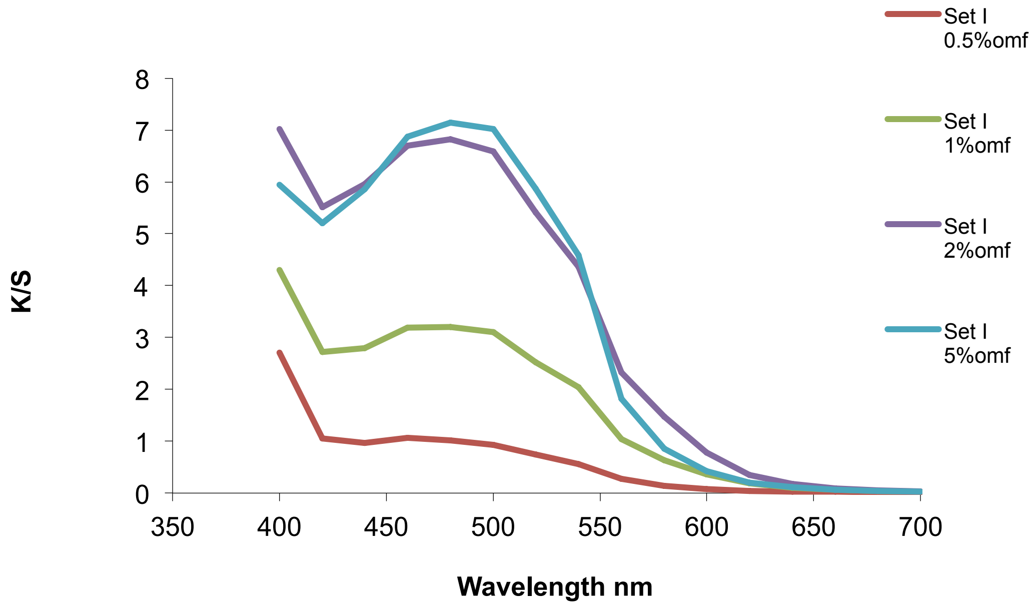

Fig. 2. K/S values of different percentages of on mass of fibre, set of dyeing I.

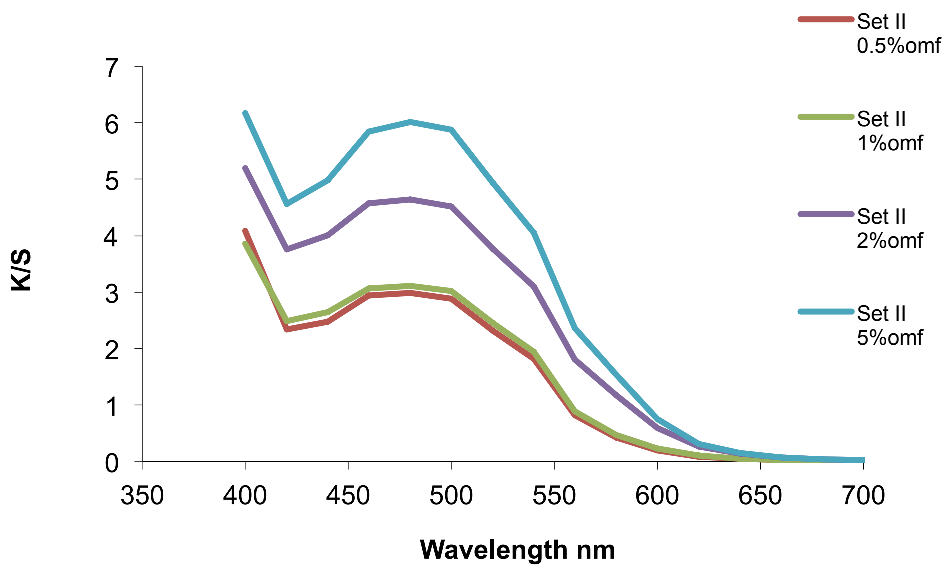

Fig. 3. K/S values of different percentages of on mass of fibre, set of dyeing II.

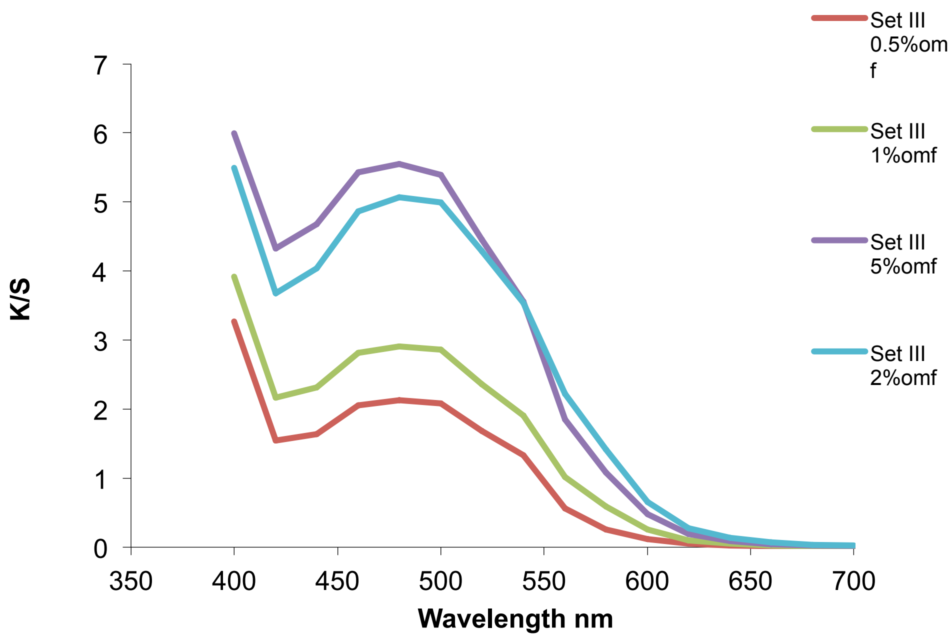

Fig. 4. K/S values of different percentages of on mass of fibre, set of dyeing III.

4. Conclusions

It is a challenging period for the textile industry, with the economic downturn threatening sales and a growing awareness of real social and environmental challenges, such as climate change, wars over resources and increasing consumer's expectations of brands.

Biotechnology's evolution takes place through significant advances in genetic engineering and synthetic biology discovering uncommon uses and functions of plants, animals or microorganisms, sometimes even replacing old industrial mechanical systems to biological ones.

The appropriation of biotechnologies exerts increasing influence in our daily lives. Technological innovation and breakthroughs in textiles are establish to meet a variety of objectives as improvement of varied species of plants used in the manufacture of fibres or their properties, production of new types of fibres, different types of dyes, effluents' management, amongst others. The recent trend of extensive use of biomaterials in product and fashion garments is growing exponentially and offers perspectives on sustainable design that assimilates science and technology, sustainable strategy and wellbeing and social innovation. Textile and fashion designers are looking at science as a tool to be used as part of the creative process allying, simultaneously, cut edge and complex technologies to serve better apparel industry in terms of quality innovative garments, increasingly trying to create textiles which lifecycle enable to adapt accordingly to the consumer's characteristics and inevitable changes - age, shape, taste, needs, etc.

Natural dyes obtained through engineered bacteria may contribute to a more ecological process to produce natural dyes and may fill the gap regarding their limited quantity providing feasibility and application on an industrial level. On the other hand, natural dyeing compounds, as Lycopene, are more biodegradable and safer.

This is the first report where Lycopene was applied to textiles. In our study, Lycopene was used to dye polyester. The obtained results suggest that the colorant extracted from fruits of Solanum lycopersium plants can be considered a potential source of natural textile dye.

Acknowledgements

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Appendix B. Sustainability and Biotechnology – Natural or Biodyes

Proceedings of the 5th Sustainability Development Symposium 2015. (Smart and Sustainable Materials) Lisbon, 15 – 17 June (ISCPS, Lisbon, PT)

Sustainability and biotechnology – natural or biodyes

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ABSTRACT:
Local is global and global is local. Globalization changed the way we view society for the past decades and it presents advantages and disadvantages. Although to be global means an increased cultural intertwining or a higher flow of information and a social tolerance as well as the existence of a world market that enables productivity and accessibility they are also disadvantages related to the loss of cultural identity of certain cultures or sustainable issues that must be addressed.
On the other hand, this new century's challenges and issues are often strongly related to the usage of non-renewable resources and production procedures putting at risk the environment and people's health.
Regarding textiles, or its resources, the growing concern over environmental quality and users health has led to a gradual interest of the reintroduction of natural dyes (and preservation of biodiversity) into the fashion and textile design industries as opposed to the current production processes.
This study analyses the evolution of natural dyes and colour throughout the centuries focusing in the sustainability of textile industry and the conservation of biodiversity, local production and ancient knowledge on dyeing techniques. It also reveals that a revival of natural dyes (and ancient/local know how) in addiction to new cutting edge technologies (such as biotechnology) allows for an industrial feasibility. Results also indicate significant reduced environmental impact and new strategies for sustainable development regarding colours for textiles.

1. INTRODUCTION

1.1 Textiles and sustainability

Globalisation surely has many advantages - increased cultural intertwining (thus more acceptance and social tolerance), higher flow of information, vast market enabling production and so on. However, it has also created a set of challenges that must be addressed urgently (Klein, 2000).

People and lifestyle transform rapidly, and so their expectations. The past decades represent worried generations, increasingly aware of the significance of biodiversity's protection and the importance of ecological footprint's reduction (Bendell & Kleanthous, 2009).

The demand for natural products is highly observable in the market; there's an increase on organic goods' consumption, recycled and recyclable materials, non-animal tested products, etc. It is evident that the lifecycle of products, as well as their production processes, became a concern to exigent consumers, observant of sustainability issues that are presented to and from the industries (Bendell & Kleanthous, 2009; Stoddar, 2014).

Industries, in the other hand, are aware of the level of difficulty that represents attending to these necessary demands. Products integrating, simultaneously, culture, communities, environment, economy, green technologies and sustainable materials are a real challenge.

Textile industry is a vast world, with many materials and techniques employed. Involving one of the longest and most complex and difficult chains in manufacturing, it is one of the most pollutants sectors in the world. It contributes a great deal to poor labour conditions, non-renewable energy and water waste, contamination and environmental impact (Klein, 2000; Braungart & McDonough, 2002; El-Haggar, 2007). Some of its most problematic facets are the finishing processes such as dyeing (Fletcher, 2008). Common dyeing processes involve the usage of fossil generated energy and heavy amounts of water. In addition, their effluents are a massive environmental concern when not conveniently treated before being released into natural waters (Malik, Grohmann & Akhtar, 2014).

1.2 Dyeing processes and challenges

Dyes represent a massive industry. Aware of the colour's influence over consumers, the textile and fashion industry explore this aspect in great detail, spending massive amounts of energy and money in the pursuit for the perfect colour. This is crucial so the product projects an intended message to increase sales (Davis, 1992; Scully & Cobb, 2012). Dyes' commercial availability is enormous and their process is one of the most fundamental aspects of textile industry commercial success; these must also be economical, available in high quantities and in diverse shades of colour. The higher demand for these compounds originated the synthesis of many millions of dyes in the past century (Clark, 2011).

Besides the pattern/printing, consumers demand for basic characteristics in textiles: high level of colourfastness regarding light, washings and perspiration. The colour must be uniform and of a solid shade throughout the substrate (Clark, 2011). To guarantee these properties, the substances conferring colour to fibres must present high affinity with the substrates. These are factors depending on the substrate texture or composition as well as on treatments applied previously or after the dyeing process (Malik, Grohmann & Akhtar, 2014; Clark, 2011).

Dyes do possess proprieties rendering them susceptible to be manipulated or altered by an infinite number of chemical agents (mordants) Additionally, these properties are vital to help creating permanent bonding with fibres. These dyeing substances also differ from each other; they must be applied in different ways, through varied distinctive methods to produce colours in certain substrates (Bancroft, 2008; Malik, Grohmann & Akhtar, 2014). Regarding dyeing application procedures, exhaust dyeing (batch), continuous (padding) and printing are amongst the most common used ones (Clark, 2011).

Dyeing matter possesses peculiar chemical properties that make it very distinct from other materials. This is the backbone of the dyeing process and the reason why colouring substrates is such a complex subject. There are, currently, thousands of different types of dyes, in the textile industry alone - a justified amount, as each fibre to be coloured requires dyes with specific features (Zollinger, 1991; Zollinger, 2003). However, the extent usage of chemicals and water waste by the textile industry is an emergent ecological concern (Malik, Grohmann & Akhtar, 2014).

Regarding the usage of water, there are, normally, two types of wasted water during dyeing. One is the dye bath, which contains the remaining dye as well as other complex compounds that helped the bonding between colouring substance and fibre Clark, 2011). These residues and the amount of dye lost vary, depending on the type of dye used and variations of pattern and colour combinations. The other type is the wash/rinse water, a procedure to remove any excess dye present in the substrate. In addition to this, water is also needed to clean all the manufacturing components involved in the process (Malik, Grohmann & Akhtar, 2014)

These effluents are generally thrown into pure clean waters, representing one of the most critical environmental challenges. These contain hazardous substances that are easily able to reach reservoirs and water treatment stations. Some of the chemicals are harmful, toxic, carcinogenic, mutagenic, corrosive and irritant (Christie, 2007; Malik, Grohmann & Akhtar, 2014) some are known hormone disruptors whilst others can affect the reproductive system (Dirty Laundry, 2011). Many of these do not break down in the environment, but instead build up in the body of animals and humans, creating mutations (Clarke & Anliker, 1980; Weber, 1993; Christie, 2007; Malik, Grohmann & Akhtar, 2014)

2. SUSTAINABLE DESIGN

2.1 Bioresources – textile natural dyes

Designer and consumer's expectations towards sustainability in the textile field and their awareness of the issues surrounding current production processes triggered some consideration on matters such as climate, environment and health (Bendell & Kleanthous, 2009, Stoddar, 2014). The preference for organic materials has, thus, increased. This has led to the reintroduction of ancient dyes in the market, natural dyeing colorants known for their biodegradable nature and less toxic features (Glover, 1995)

These ancient dyes are obtained through biological resources, usually plants or animals, and were used as far back as two thousand years ago. A dye is a coloured compound extracted only through physical-chemical (dissolution, precipitation, amongst others) or biochemical (fermentation) processes. This coloured substance must be soluble in an aqueous solution (dyebath) in which the material to be dyed is soaked in (Clark, 2011). Natural dyes are perceived as safer due to their higher level of affinity with the environment, thus, causing less impact. Some can provide for high quality dyeing, great colourfastness properties and bright colour shades (applied with our without mordants).

Some of the known natural dyes also contain many properties appealing to the most of us, consumers. They are eco-friendly compounds, possessing medicinal advantages such as antimicrobial (Prusty, Trupti, Nayak & Das, 2010; Singh, Jain, Panwar, Gupta & Skhare, 2005) and anti-inflammatory properties (Hamburger, 2002). Besides, clothes dyed with natural dyes revealed a higher level of protection against UVR than the ones dyed with synthetic ones (Hustvedt & Crews, 2005; Kozlowski, Zaikov, & Pudel, 2006).

2.2 Natural colorants implementation

However, whilst nature is teeming with coloured compounds, not all that nature provides can be used in dyeing. Only a small percentage of these natural substances are applied to textiles - mostly deliver dull, uneven hues and poor fastness, when washed and exposed to light or perspiration. Most natural dyes still unspecified in terms of fastness properties and methods of extraction, production and application involved. As varied studies indicate, there's great need for research to overcome issues related to the implementation of natural dyes in modern dye houses, particularly regarding efficient dyeing recipes and their variations (Bechtold, Turcanu, Ganglberger & Geissler, 2003).

Additionally, the amount of dyestuff and colour shades provided is very limited. Dyeing with natural dyes is, consequently, highly costly. This class of colorants involve rather complex processes - long and difficult extraction methods and a high level of difficulty to produce and apply in order to obtain a quality dyeing. To better deal these aspects, varied studies suggest technologies such as ultrasound methods of extraction (Sivakumar, Vijaeeswarri, Anna, 2011) and application (Vankar, Shanker, Dixit, Mahanta & Tiwari, 2008), or less water usage procedures to reduce the ecological footprint of finishing processes (Dyecoo, 2014).

Although all the natural dyeing substances' benefits and the significant interest of their re-introduction in the market, the challenges around scaling such compounds are complicated. Besides, transferring traditional natural dyeing methods to a modern dye houses require intricate experimentations or redesigning already implemented systems (Leitner, Fitz-Binder, Mahmud-Ali, Bechtold, 2012).

As mentioned, dyeing is a complex process involving chemical and physical occurrences. By the time of synthetics dyes' introduction to the market dyeing with natural dyes became an obsolete practise and most knowledge on techniques and procedures were lost. In addition, there is an extensive amount of data that has yet to be recorded; one still knows very little about what can biodiversity provide or which biological resources possess dyeing potential material. Recent studies prioritise the search for new biological resources, identifying new species of fauna and flora producing substances with dyeing potential (Department of Biotechnology, 2005). The significance of such data lies on the hypothesis of certain isolated coloured compounds to be tested in textile fibres, to better evaluate their dyeing efficiency, hence applied to the industry. Again, further research on the subject is imperative and will be determinant to overcoming sustainability issues in the textiles sector.

These are a few reasons why natural dyes' usage is such a challenging subject for the industry. Although presenting many beneficial properties, its viability at a massive industrial scale is, so far, not easily attained. These demands call for finding alternatives in sustainable dyeing and radically new ways of creating and manufacturing materials as well as deeper scientific research.

3. BIOTECHNOLOGY TEXTILE – SUSTAINABLE MATERIALS

3.1 Alternatives in product design and manufacturing

Textiles' sustainability issues are gradually being exposed and debated. Legislation is emerging as more demanding and pollution control boards are progressively restricting guidelines for the textile industry. General targets are synthetic dyes' production, application and related effluents; their usage represents serious toxicological issues and a threat to the ecosystems and human health (Clarke & Steinle, 1995; Vandevivere, Zaikov & Pudel, 2011).

Until fairly recently, manufacturers focused attention on industry elements that would enable quick profit (maintaining final product's cost low or efficiency in production). Emerging design strategies in sustainable and responsible design question the current systems of manufacturing considering aspects like environment, consumers and technologies.

Some fashion designers and brands have adopted a conscious, attentive and critical position towards sustainable issues, integrating human well-being and green philosophies at the core of their corporate identity (Bendell & Kleanthous, 2009). These companies, generally part of the slow fashion movement, provide design prepared to sustain communities, encourage and support local employment while, simultaneously, aiming towards environmental protection. They represent local production, raw materials such as natural dyes or fibres and traditional know how by producing and resourcing locally (*Awamaki Lab,* 2012; Ecouterre, 2012).

Environmentally, is of great significance that designers and manufacturers understand, in greater depth, the lifecycle and real capital of products being created. It is mandatory that designers/brands generate strategic and tactical approaches to design process and question how can goods be projected and manufactured to better serve and suit consumers, and the planet. Aspects such sustainable improvement, environment, consumer's values, wishes and needs must be taken into account as well as the search for radical new production alternatives, to efficiently meet the requirements of this new century (Niiniaki & Hassi, 2011).

It is crucial to examine the possibilities of new substances or materials emerging as well as new manufacturing methods and potential impact on the world. It is no longer only about resources exploitation but also about providing, through products, wellbeing and social improvement. Furthermore, is about providing consumers with highly smart and eco-friendly products and materials; creating goods or textiles which lifecycle enables to adapt accordingly to the consumer's characteristics and inevitable changes - age, shape, taste, needs, etc (En Vie, 2013; Grow your own, 2013).

The scope of science currently allows for a completely new radical way of rethink materials or for innovative methods of producing. With increasingly more technological innovation and breakthroughs as well as collaborations between scientists and designers the world has been noticing the intensification of biotechnologies as the foundation (green strategies) of many sustainable design projects (Myers, 2012).

3.2 Bio-cooperation - biotechnology impact on the world

Biotechnology application in textiles dates back over two thousand years - from fibres to natural dyes (Biocouture, 2010; Kandra, Challa & Jyothi, 2012, Ginsberg, 2011); more recently, the management of residual waste, by microbes (Novotny, Svobodová, Benada, Kofronová Heissenberger & Fuchs, 2011). The leap from classic to modern biotechnology involved only the ideal innovative tools to discover different uses and functions of bio resources, thus allowing for the improvement of this new field (Church & Regis, 2014). These sophisticated technologies' evolution is accentuated through significant advances in genetic engineering and synthetic biology, where the use of living organisms are understood as a biological process that may replace industrial or mechanical systems (Synthetic Biology Project, 2014)

Synthetic Biology is, in broader terms, the engineering of biology. Its purpose is to make biology available to the requirements of everyday life, considered as highly effective to overcome environmental issues and tackle pollution (Schmidt, 2012).

Bio resourced technologies' increase is rapidly transforming the world with its infinite number of applications and possibilities; biotechnological processes play a key role in increasing and promoting sustainable production. In the Design or Textiles fields, biotechnologies' practices are normally associated with sustainable development and green manufacturing processes - pollution control and prevention, resources conservation, cost reduction. This approach enables for a new radical way of rethinking materials (Schmidt, 2012) as it consists in building new biological functions or systems or re-designing existing natural ones (Synthetic biology org). The production of biomaterials is a significant impact of this technology (Schmidt, 2012).

Textile and fashion designers are looking to science as part of the creative process, producing unique and often surprising results (En Vie, 2013; Grow your own, 2013). Cut edge and complex technologies serve better apparel industry in terms of quality innovative garments. Although most technology is considered underexplored, the recent trend of extensive use of biomaterials in product and fashion garments is growing exponentially, given their possibilities.

3.3 Bioresourced colorants – natural and bio dyes

As mentioned, natural dyes possess many benefits, particularly for consumer's health and the planet. However, their extraction, production, application and implementation are rather complex, not to mention the lack of knowledge surrounding techniques and bioresources. Nevertheless, some issues regarding their usage might be attenuated through cut edge, sophisticated, technologies such as modern biotechnology. Additional sustainable alternatives to toxic synthetic dyes consist in the use of fibres possessing natural colour (classic biotechnology) or modified to do so (modern biotechnology).

We are already familiarised with natural colorants to dye (from fauna and flora) or naturally dyed cotton fibres (pale shades of brown, beige, green, red), both used since ancient times (Vreeland, 1999, Ecouterre, 2012). There's also reference in the literature to silkworms producing naturally wide-ranging coloured silk fibres, when manipulating their diet or environment (Ecouterre, 2011). Another example can be analysed in the Madagascar's origin Orb Weaver Spider producing silk fibres that are naturally golden dyed (Guardian, 2012). Such choices are effective to decrease energy and water waste, saving fibres from most of textile finishing procedures. Other naturally dyed fibres consist in genetic engineered experiments (Chen, Wang, Hua & Du, 2007), with varied coloured silk fibres being produced.

Following the biological technologies approach, there's also the production of coloured compounds through a rather unusual mediums – microorganisms or microalgae (The Guardian, 2015). This is a phenomenon that occurs naturally in nature, often found in different plants' microsystems (rhizosphere) or glaciers (Lu, Wang, Xue, Zhang, Xing, Lou, Zhang, Li, Zhang, Bi & Su, 2009), etc. Manipulating at times their environment, different colour shades can be produced (En-vie, 2014; Ecouterre, 2015)

This mechanism, using living bacteria to produce substances, might be considered as a sustainable strategy for dyes' mass manufacture, creating less-environmentally damaging materials (Zhao, 2013).

Its effectiveness finds in Synthetic biology a way to enable the production of specific dyes designed to meet the industry's demands and consumer's expectations. Microorganisms can, not only grow rapidly but also, be programmed to provide varied dyes with different properties and different colours, being simultaneously cost effective.

Some pigments created through bio machines were already isolated in lab. *"E-chromi"* is one of such projects, born from the collaboration of scientists and designers who genetically engineered bacteria to secrete a variety of coloured pigments, visible to the naked eye. Standardised sequences of DNA (biobricks) were designed and inserted *into E.coli* bacteria enabling for the production of colours such as red, yellow, green, blue or violet, possibly allowing for its application on textiles (Ginsberg, 2012).

The usage of sophisticated technologies, such as Synthetic Biology, contributes to profound transformations in the sector and to the concept of Design itself. Its impact will, surely, invite new scenarios and generate vital debating (Myers, 2012). As we are slowly capable of manipulating nature and build things with biology, we are increasingly witnessing a new era in Design, manufacturing products and producing materials that empowers for a more sustainable future (Zhao, 2013)

4. CONCLUSION

It is a challenging period for the textile industry, with the economic downturn threatening sales and a growing awareness of real social and environmental challenges, such as climate change, wars over resources and increasing consumer's expectations of brands.

One of the most complex aspects of the industry is the dyeing process. It is one of the most pollutant components of textiles with a heavy ecological footprint. Toxicity, water waste and contamination, non-renewable generated energy consumption, health hazards for humans and ecosystem in general, etc.

Awareness on environmental issues has led to the interest of natural dyes reintroduction in the market. Although having many benefits, the reality is that their implementation on a massive industrial scale is rather incompatible to the needs of manufacturing. Industry demands for a great variety of colour shades as well as high quality colourfastness as well as economical dyes - vital requirements for commercial success. Additionally, natural colorant dyeing techniques, and bio-resources involved, lack deeper research. Nevertheless, with the significant improvements on biotechnologies witnessed during the last decade, some fundamental alternatives might be considered.

The appropriation of biotechnologies exerts increasing influence in our daily lives. Technological innovation and breakthroughs in textiles are establish to meet a variety of objectives such as improvement of varied species of plants used in the manufacture of fibres or their properties, production of new types of fibres, different types of dyes, effluents' management, amongst others. Environmental biotechnology (white and brown biotechnology) and specially Synthetic Biology, plays a key role in increasing and promoting sustainable production.

Textile and fashion designers are looking to science as part of the creative process, producing unique and often surprising results (En Vie, 2013; Grow your own, 2013). Cut edge and complex technologies serve better apparel industry in terms of quality innovative garments; the recent trend of extensive use of biomaterials in product and fashion garments is growing exponentially, given their possibilities. Their contribution is vital to sustainable development or green manufacturing processes – prevent pollution, reduce costs and resource's conservation.

Sometimes introducing visionary and radical strategies for improving the performance of objects around, biotechnology multiple applications are focused and designed to deal with sustainable development and core industrial issues. The possibilities of such technologies suggest different approaches on responsive design assimilating science and technology, the environment, sustainable strategy, wellbeing and social innovation.

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Ergonomic Fashion Design - Sustainable Dyes

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ABSTRACT

Water waste, contamination, and fossil fuel generated energy are acknowledged issues within the textile industry. Current dyeing processes pose serious threat to the environment and human health, often associated with toxic and carcinogenic substances that are released into the environment, through effluents not conveniently treated before being discharged into natural waters. Besides print and pattern, consumers demand for basic characteristics in textiles – these must resist to agents that cause colours to fade. On the other hand, industry must provide a great range of colours and access to huge quantities of coloured substance to dye. Simultaneously, it must be cost-effective. Natural dyes are perceived as less harmful for the environment due to its biodegradable nature. Studies reveal certain natural dyes possess UVR protection properties, as well as antimicrobial and anti-inflammatory assets. Nevertheless, depending on the nature of the dye, there are many advantages and disadvantages to consider.
Through an extensive study on various fields such as Biotechnology, History, Ethnography, Biology, Archaeology, amongst many others we gathered information regarding natural coloured compounds, colour sources (plants, animals and microorganisms), ancient and modern techniques of extraction and application. This study shows the evolution of dyes throughout the centuries. It also reveals that the revival of natural dyes in addiction to new cutting edge technologies such as biotechnology might allow for an industrial feasibility.

Keywords: Sustainability, Dyeing, Innovation, Biotechnology textile, Colours, Ergonomics

INTRODUCTION

It is a challenging period for the textile industry, with the economic downturn threatening sales and a growing awareness of real social and environmental challenges, such as climate change, wars over resources and increasing consumer expectations of brands.

Textile sustainability issues are often associated with dyeing methods applied by the fashion and textile industry. The negative aspects of such practices are strongly related to the usage of non-renewable resources as well as the effluents derived from these specific finishing processes. These effluents present high levels of toxicity putting at risk the entire ecosystem.

Dye's production and application process is crucial for the textile industry's success. Aware of colour influence over consumers, textile and fashion industry explore this aspect in great detail, spending massive amounts of energy and money in the pursuit for the perfect colour. This is crucial so the product projects an intended message to increase sales. Fashion design would not be such a major phenomenon without dyeing development and its techniques.

Dyeing industry is currently facing great challenges. Although having many benefits, the usage of certain synthetic dyeing substances must be analysed in greater depth for a better understanding of the real risks of its application and which are the possible alternatives, if should them be replaced. Meanwhile, certain synthetic toxic dyes have been removed from market but current dyeing processes are still characterised as little sustainable. The main reason for this resides in the hazardous chemicals from textile effluents (during the finishing processes) that are not conveniently treated before discharge. These chemical substances pose great threat to human's health and entire ecosystem by being able to easily infiltrate water treatment stations and reservoirs (Vandevivere et al 1998); they are considered harmful, toxic, carcinogenic, corrosive and irritant; some are known hormone disruptors, whilst others can affect the reproductive system. Some toxic substances do not break down when in the environment but instead build up in every living organism causing mutations (Dirty Laundry, 2011). They are considered non-safe for consumers (Clarke and Anliker, 1980) and the environment (Clarke and Steinle, 1995). Severe risks to consumers are associated with the length of time of exposure to it, oral ingestion, skin and respiratory tract susceptibility (Clarke, Steinle, 1995). Water is becoming increasingly contaminated and studies reveal that almost two tons per day of these chemicals are thrown into the environment (Anliker, 1978).

METHOD

For deeper understanding on such subjects, the methodology used in this study consists essentially on the analysis of scientific papers and books, thus, primary and secondary research. Documents include articles on many subjects in fields of knowledge as different as design, history, ethnography, anthropology, chemistry, biology, among many others; these documents were imperative for the identification of different natural coloured substances, and by crossing these different topics we were able to gather data regarding the identification of the main dye's bio sources and provenience, extraction methods, ancient techniques, procedures of application, possible shades and dyeing evolution. This research covered developmental stages of many different civilizations and reflects upon many technologies involved in either the dyeing procedures or its evolution and enhancement.

RESULTS AND DISCUSSION

Solving some of the negative features of dyeing is not an easy task mainly because there are two important aspects that need to be considered. One is associated to the consumer's demands; the other is related to the textile industry needs.

Besides print and pattern, consumers demand for basic characteristics in textiles: resisting to the agents that cause colour to fade, great range of colours, safety, etc. For colours to resist usage, light, perspiration and washing, dyes conferring colour to fibres must present high affinity properties allowing for a greater fastness and uniformity. On the other hand, industry needs are related to the vast range of colour shades it intends to sell and the huge quantities of dyestuff required for large scale dyeing. Dyes must, simultaneously, be economical. Currently one can find approximately two thousand different types of synthetic dyes on the market (only in the textile industry) (Zollinger, 1991). This number is justified given the requirements of industry and consumers as well as the quantity and characteristics of the fibres, which require dyes with specific features.

Due to the hazardous aspects of dyeing, the prompt response by consumers and professionals (generally brands embracing principles of s*low fashion*) aware of such issues is a preference for natural products, generally safer but at the same time more costly. This preference led to the gradual interest and reintroduction of natural dyes in the market. Due to their biodegradable nature, natural dyes are generally considered safer. They possess a higher level of affinity with the environment causing less impact. Depending on which natural dye, some are known to possess great colourfastness properties (applied with or without mordents), fair range of colours, protection properties against UVR (Kozlowski, Zaikov and Pudel, 2006) as well as antimicrobial (Prusty, Trupty and Das, 2010 / Singh, et al. 2004) and anti-inflammatory advantages (Hamburger, 2002). These are not without disadvantages, though.

Despite the vast array of coloured compounds found in nature, reality is only a small parcel of it is used to dye (table 1). There's an extensive amount of data that were lost at the time of the introduction of synthetic dyes in the market. Within this class of dyes, most knowledge on resources, extraction techniques and applying methods is very limited. Naturally, dyeing with natural dyes tends to be expensive due to their rather complex processes of extraction and application and the very limited amount of dyestuff provided. Within this context, it is crucial a deeper understanding on materials, dyes and fibres, and also a focus on learning more about the vast biodiversity yet to be explored. Knowledge on bio-resources is vital to push boundaries on applicable research within the sector.

Table 1: Natural coloured compounds with great dyeing potential (Santos, 2010)

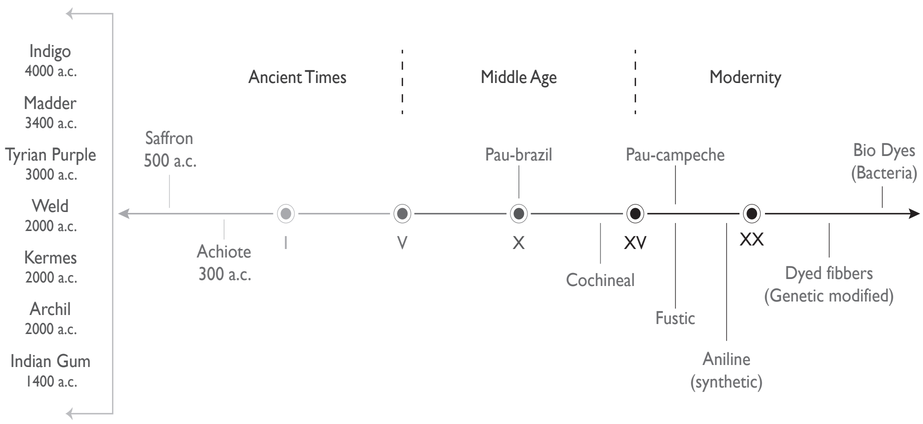

Figure 1. Speculative timeline on natural dyes and its hypothetical evolution. (Santos, 2010)

Regarding dyeing industry, specifically, some of the alternatives consist in the use of living organisms, providing clean technologies and helping dealing with environmental issues (Ratledge and Kristiansen, 2001). Biotechnology (either classic or modern) makes use of bio-resources in order to create products for the benefit of man (Nair, 2008). This approach is not innovative though - societies always depended on biotechnology (classic or traditional) to obtain new products or substances of interest, e.g. bread, beer, natural dyes, etc. A fair amount of work is reported, particularly in the treatment of textile effluents with microbes. Ecologically, in the past decades, bacteria are most important for the restoration of a contaminated environment. This specific process of bioremediation is an economical, versatile, environment friendly and efficient treatment strategy, rapidly developing technology to degrade or detoxify chemical substances.

Additional sustainable alternatives consist in the use of fibres possessing natural colour (classic biotechnology) or modified to do so (modern biotechnology). There's reference to various different types of silk worms producing different coloured silk fibres (Chen, Wang, Hua & Du, 2007). Another example can be analysed in the Madagascar origin Orb Weaver Spider; through the discovery of a specific arachnid producing silk fibres with such properties, a natural golden emerges in the silk cape shown in figure 2 (no dyeing process involved). This option is effective for energy and water waste, saving fibres from most of textile finishing procedures.

Modern biotechnology (genetic engineering and synthetic biology) is a rather radical form of approach but it is standing out as a future alternative for many sustainability related issues, slowly replacing industrial or mechanical systems with a biological process. Synthetic biology is increasingly finding new ways to integrate into the everyday life, especially when combined with Art and Design. Questions arise though and, through the creation of varied projects, these fields alert for the endless possibilities of these new technologies.

Biotechnological materials are becoming very much of a trend in the past recent years. They introduce visionary strategies for improving the ecological performance of objects; with new emerging fields such as synthetic biology, sustainable issues are much promptly to be solved. It is relevant for the dyeing industry bacteria specifically engineered to produce better quality dyes (bio-dyes) (Ginsberg, 2012).

The reuse of dyeing bath or waterless dyeing techniques (to reduce waste), ultrasound techniques (to enhance the bond between dyes and fibres) and others were also considered in this study as complementary alternatives.

CONCLUSIONS

Dyeing process represent one of the main challenges for the fashion and textile sectors. Current dyeing procedures pose serious threat to the environment and human health, being classified as little sustainable. As a result, research and development strategies within this industry and fashion design are now highly focused and the challenges will force many transformations in the sector.

Both natural and synthetic dyes possess advantages and disadvantages when applied industrially. The former do not always guarantee infinite shades of colour and large quantities of material (so that they might be used in bulk), therefore natural dyeing cannot be practical in a large industrial scale. They are also expensive due to their rather complex extraction methods. Synthetic coloured compounds are related to toxic and ecological issues, which must be contained. Some authors defend that these are issues that can be circumvent by the use of sophisticated technologies such as modern biotechnology.

Natural dyeing is associated with green methods because natural compounds present a biodegradable nature and less toxicity. Some studies show that some of the natural dyes used in ancient times possess suitable fastness properties. Additionally they are more effective protecting the skin against UVR and hold medicinal properties. Surely, natural dyes and potential biological resources need to be explored in greater depth; knowledge on resources and techniques can be allied to other technologies in order to enhance their dyeing potential. This way there's a chance they become of important use for the textile and fashion industry (large scale), not only for *slow fashion* movement embracing design companies.

Currently, there are techniques that allow for the manipulation and modification of living organisms. Through genetic engineering the gene that contains the genetic code for the production of a substance of interest can be transferred to another organism (Ratledge and Kristiansen, 2001). This organism will then start to produce large quantities of the same substance even if it has never produced it before.

Modern biotechnology also ensures other alternatives for the production of potential textile dyeing colourants. Synthetic biology is another approach that offers way to engineer bacteria to produce bio-dyes that can be implemented by the fashion and textile industry. Another approach is to confer colour to the fibre at its core in the same way naturally dyed fibres, like pale colour cottons or golden spider's silk threads appear in nature. Via modern biotechnology it is possible to confer an infinite range of colours to different types of fibres and studies refer advances for blue cotton as an appropriate approach for the creation of ecological fashion design garments. This allow for the elimination of toxic dye's application during finishing process, reducing the incidence of ecosystem damage caused by dyeing procedures. Ethical questions are likely to be raised, though.

Biotechnology's application in the textile and fashion design sectors suggests methods that result in less waste for the ecosystem and use less energy and water, thus, becoming an important and highly promising approach to pollution's prevention and decline, as well as aiding biodiversity conservation and cost reduction. Plus, it means that the application of natural textile dyes can be done in bulk and is therefore feasible on an industrial scale.

Dyes derived from plants, animals or microorganisms surely have limitations. Nevertheless, studies illustrate the importance of modern biotechnology to enhance the dyeing potential of certain coloured substances or even to produce new substances of interest that better fit the need and demands of textile industry. This study shows the evolution of dyes throughout the centuries. It also reveals that the revival of natural dyes (and technical knowledge attached to it) in addiction to new cutting edge technologies such as biotechnology might allow for an industrial viability.

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Appendix D. Sustainable colours and biotechnology in the fashion and textile industry

Proceedings of the 12th International AIC2013 Congress - Association Internationale de la Couleur. Newcastle, United Kingdom, 8-12 July 2013. Edited by L. MacDonald, S. Westland & S. Wuerger. pp 152. ISBN 978-0901623027 (The Sage Gateshead - Newcastle, UK)

Sustainable Colours and Biotechnology in the Fashion and Textile Industry

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Abstract

Textile sustainability problems are often associated with the dyeing methods applied by the fashion and textile industry. These issues are strongly related to the usage of non-renewable resources as well as the effluents of such finishing processes that present high levels of toxicity and risk for the entire ecosystem. These effluents discharges are still thrown into natural waters poisoning them with substances that don't break down in the environment but instead grow and mutate in every living organism. The growing concern over environmental quality and consumers health has led to a gradual interest on the reintroduction of natural dyes (and preservation of biodiversity) into the fashion and textile design industries as opposed to the current production processes. Through an extensive study on various fields such as Biotechnology History, Ethnography, Biology, Archaeology, amongst many others we gathered information regarding natural coloured compounds, colour sources (plants, animals and microorganisms), ancient and modern techniques of extraction and application as well as advantages and disadvantages of dyes (natural and synthetic), etc. This study shows the evolution of colour in the textile industry throughout the centuries, since ancient times until modern days. It also reveals that the revival of natural dyes in addition to cutting edge technologies such as biotechnology allows for an industrial feasibility. Results indicate significant reduced environmental impact and strategies for sustainable development.

1. Introduction

Since young age we are surely conditioned to react to colours in both emotional and psychological ways. Aware of colour influence over the consumers, textile and fashion industry explore this aspect in great detail, spending massive amounts of energy and money in the pursuit for the perfect colour. This is crucial so the product successfully sends an intended message in order to increase sales. Fashion wouldn't be such a major phenomenon without dyeing development and its techniques. By reconstructing its history and evolution we can better evaluate their sustainable potential as well as realize if they contain key answers for current or future issues that seek resolution in the fashion and textile industry (Hamburger, 2002).

Natural dyeing was always of major importance until the middle of nineteenth century when the first synthetic dye was discovered (Garfield, 2002). This encounter led to the gradual abandoning of natural dyes usage due to their high prices and rather complex technologies involved (often characterised by lengthy procedures and a higher level of difficulty regarding methods of extraction and limited shades and fastness). Synthetic dyes offered industry a great variety of colours, great fastness properties, plus they were cheap. This innovation made possible the usage of textile dyes in bulk, however, the production and application of some of them represent severe ecological and toxicological risks. This aspect is certainly one of the most serious problems in the textile industry, seeking for an urgent answer. Alternatives must be discussed.

2. Method

For deeper understanding on relevant subjects, the methodology used for this study consists essentially on the analysis of scientific papers and books (primary and secondary research). Documents include articles on many subjects in fields of knowledge as different as design, history, ethnography, anthropology, chemistry, biology, among many others; these documents were imperative for the identification of different dyes; by crossing different topics we were able to gather data regarding dye's bio resources, provenience, extraction methods, ancient techniques, procedures of application, possible shades and evolution. This research covered developmental stages of many different civilizations (until the 21st century) and reflects upon many technologies applied involved in dyeing procedures or its evolution and enhancement.

2.1 Natural dyeing survey and biotechnology approach

There is very limited literature that can assure us accuracy on dates and methodologies, regarding dyeing. Also, there is not much information left on ancient techniques and extraction methods or which biodiversity one should search for resources. By researching different fields of knowledge we were able to trace a certain amount of documents in order to gather data regarding coloured substances, information on bio resources, origins, availability, shades, techniques and methods involved in their production or application.

As a technology that makes use of bio resources in order to create products for the benefit of man (Nair, 2008), biotechnology is, in the last decades, also used to provide clean technologies and to deal with environmental problems (Ratledge and Kristiansen, 2001). Living technologies must be fully explored, and analysed in greater depth, allowing industry to better benefit from them. We focused this study in both advantages and disadvantages of biotechnology for a more sustainable dyeing procedure.

3. Results and Discussion

Guidelines for textile industry by the pollution control boards question their sustainable practices. As a highly competitive business, the prime concern of textile industry is to develop greater awareness of quality and sustainability while effectively responding to industry and consumer's demands. Innovations in its procedures are imperative for sustainable strategies to be implemented.

The production of dyes is an indispensable process within the textile industry success. Besides the print and pattern, consumers demand for basic characteristics in textiles. These must resist to the agents that cause colours to fade. Textile dyes must then guarantee colourfastness. They must, simultaneously, be cost-effective. Despite the many benefits, the production, application and usage of certain textile dyes are not safe for consumers (Clarke and Anliker, 1980) and for the environment (Clarke and Steinle, 1995). The effluent textiles derived from their usage contain chemicals are harmful, toxic, carcinogenic, mutagenic, corrosive, and irritant; some are known hormone disruptors, whilst others can affect the reproductive system. Many don't break down in the environment, but instead build up into the bodies of animals and humans, generating mutations (Dirty Laundry, 2011). The use of some synthetics dyes carries severe risks for consumers. These are related to length of exposure, oral ingestion, skin and respiratory tract susceptibility (Clarke, Steinle, 1995). Recent changes in legislation plus emergent awareness of consumers triggered a preference for natural quality products (Luxury Fashion, 2009), which led to an awakening interest for natural colour compounds.

Natural dyes are perceived as less harmful for the environment due to its biodegradable nature, therefore safer for consumers and ecosystem in general. Studies reveal certain natural dyes are of great efficiency regarding to colourfastness and UVR protection (Kozlowski, Zaikov and Pudel, 2006). Furthermore, some possess antimicrobial (Prusty, Trupty and Das, 2010 / Singh, et al. 2004) and anti-inflammatory properties (Hamburguer, 2002). Their application is more frequent within brands that embrace principles of *Slow Fashion*; initial problems related to the scarce usage of natural dyes are often associated with lack of knowledge on resources, extraction processes and dyeing methods (Shamim and Karmakar, 2006). Naturally, these compounds are still limited in quantity and thus remain expensive.

Biotechnology is particularly important when analysing the evolution of dyeing. By allying ancient knowledge and innovative methods, dyeing processes may be improved; research indicates positive results of great quality considering the purposes of industry regarding colourfastness (Vankar et al. 2008). Additionally, through genetic engineering, it is possible to enable an organism to produce large quantities of a certain coloured compound of interest (Ratledge and Kristiansen, 2001/Hasseloff, 2012) reducing the incidence of ecosystem damage caused by dyeing and finishing procedures. Also it is possible to produce natural dyed fibres with much more convenient colour shades for the industry (Chen et al., 2007) eliminating the dyeing process (Santos, 2010). Furthermore, experiments still need to be made in order to quantify and understand the dye potential of these bio-dyes, though ethical questions are likely to be raised (Ginsberg, 2012).

4. Conclusions

Both natural and synthetic dyes possess advantages and disadvantages when applied industrially. Natural coloured compounds do not always guarantee infinite shades of colour and large quantities of material. They are also expensive due to their rather complex extraction methods. Therefore, natural dyeing cannot be applied on a large industrial scale. Some synthetic dyeing substances are related to toxic and ecological issues, which must be contained. Some authors defend that these are issues that can be circumvent by the use of sophisticated technologies such as modern biotechnology.

Natural dyeing is associated with green methods. They possess a biodegradable nature and less toxicity and fair fastness properties. Additionally they hold UVR protection and medicinal properties. Surely natural dyes need to be explored in greater depth. Biotechnology's application in the textile and fashion design sectors suggests methods that result in less waste for the ecosystem and use less energy and water. Despite being such a radical form of approach, it is a promising technology to pollution's prevention and decrease, biodiversity conservation and cost reduction. In sum, this means that the application of natural textile dyes could be done in bulk and would be, therefore, feasible on an industrial scale.

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Appendix E. Biotechnology and sustainability in the Fashion Design Industry: natural textile dyes

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ABSTRACT: In the last decades environmental issues have gradually become more critical and frequent, mainly due to the population overgrowth and increased industrial activity. Water pollution is certainly one of the major problems in modern society. Within this context one must focus on the textile sector and on how to circumvent the main problem it currently faces – the use of toxic synthetic dyes. The revival and knowledge of natural dyes, allied with cutting edge technology, triggers possibilities that may result in helping to narrow down the environmental impact or lead to new strategies within sustainable development. For an effective use and application of natural dyes, one must have a profound knowledge of the available sources and of the biodiversity yet to be explored. Natural dyes can work as an alternative to toxic synthetic coloured compounds. Further more, using today's sophisticated technologies one can optimise their application, providing the textile and fashion design industry with a vast array of solutions to the resolution of inherent problems and necessities.

Keywords: Natural dyes; Eco Design; Industrial sustainability; Biotechnology textile; Dyeing process

Introduction

As professionals and *consumers*, analising and acting within and for society, both rationally and intuitively, one must assume a critic position and be aware of the environmental actions within it.

Dyeing and printing with natural dyes was always fundamental to the art and cultural identity of people. Dye is a coloured substance used to assign permanent colour to other substances. Its most important application is the dyeing of textile fibres, yarns and fabric. Dyes can be divided in two different groups – natural dyes and synthetic dyes.

Synthetic dyes appeared in the 19th century (Garfield, 2002) and to date one can find approximately more than 2000 types of synthetic dyes in the textile industry alone (Zollinger, 1991). Their commercialization has withdrawn, almost entirely, all of the natural dyes from the market. Nonetheless, their current application and use as well as their effluent discharges cause severe environmental issues and represent toxicological risks for the consumer

(Vandevivere, Bianchi & Verstrate, 1998).

This problematic subject caused a natural dye revival and increased awareness and research of the biodiversity available to resource such dyes (Department of biotechnology, 2005). Due to their biodegradable nature, natural dyes possess a higher level of affinity with the environment (Bhuyan, Saikia & Das, 2004) and have great dyeing potential.

This study aims to be the catalyst for eventual research that will help reduce environmental impact and open the way to new strategies concerning sustainable development within the Design and Textile industry. This will be achieved through a deeper understanding of natural dyeing compounds, their processes and techniques.

Biotechnology (classic or modern) plays a fundamental role in assessing the effective scope of environmental development (Bryce & Balasubramanian, 2004), also ensuring industrial feasibility, thus aiding the pursuit of solutions to current problems of an unavoidable nature.

Problem, Hypothesis and Method

It is necessary to develop a deeper knowledge of harmless coloured compounds, in order to resolve the main problem the fashion design and textile industries currently face, i.e. the application of toxic synthetic dyes.

Although having many benefits, production, application and usage of toxic dyes are not safe for the consumer (Clarke & Anliker, 1980) and the environment (Clarke & Steinle, 1995).

The hazardous chemicals discharged by textile effluents (clothes and dyeing/printing factories) pose a threat to human health and the environment and can easily infiltrate water treatment stations and reservoirs (Vandevivere, et al., 1998; Banat et al., 1996). These chemicals are harmful, toxic, carcinogenic, mutagenic, corrosive, and irritant; some are known hormone disruptors, whilst others can affect the reproductive system. Many don't break down in the environment, but instead build up in the bodies of animals and humans creating mutations (Dirty Laundry, 2011). The use of synthetics dyes by consumers carry severe risks that are associated with the length of time of exposure to it, oral ingestion, skin and respiratory tract susceptibility (Clarke, Steinle, 1995) Water is becoming increasingly contaminated and studies reveal that almost 2 tons per day of these chemicals are thrown into the environment (Anliker, 1978.).Therefore, more research into natural dyes (and their resources) is required and of primordial importance for the development of new coloured compounds (Bhuyan et al, 2004) capable of meeting the necessities demanded by the fashion industry and consumers as well as ecosystem and human being's protection.

Biotechnology allows for the optimization of a natural dye's application. Also, it may optimize its yeild allowing for industrial feasibility, cost and energy reduction. Biotechnology allows for the optimization of a natural dye's application. Also, it may optimize its yeild allowing for industrial feasibility, cost and energy reduction. Additionaly it provides greater dexterity to compounds that are not faced with the problems inherant to those that are currently comercialised. Biological resources provide higher protection for consumers (or those people working directly with toxic dyes), less toxicity, great affinity with the ecosystem and biodegradability - hence less environmental impact (Kozlowski, Zaikov & Pudel, 2006). The application of dyes extracted from plants, animals, or even microorganisms, is a century's old procedure (Lu, Wang, Zhang, Xing, Lou & Tiwari, 2009) and can also be improved via modern biotechnology (Vankar, Shanker, Dixit, Mahanta & Tiwari, 2008). Currently, we have techniques that allow for the manipulation and modification of living organisms. Through genetic engineering the gene that contains the genetic code for the production of a substance of interest can be transferred to another organism (Ratledge &

Kristiansen, 2001). This organism will then start to produce large quantities of the same substance even if it has never produced it before.

Presently the natural blue cotton fibre (genetically modified) allows for the elimination of toxic dyes during the finishing processes, reducing the incidence of ecosystem damage during the dyeing process. This may be an appropriate approach for the creation of ecological fashion design garments.

The application of Biotechnology in the textile and fashion design sectors signifies processes that result in less waste for the ecosystem and use less energy and water. Thus becoming an important and highly promising avant-garde approach to pollution's prevention and decline, as well as aiding biodiversity conservation and cost reduction.

Plus it means that the application of natural textile dyes can be done in bulk and is therefore feasible on an industrial scale.

The methodology used in this study consists of research and analysis of archeological, ethnological and historical documents, imperative for the identification of different natural colorant compounds (concerning the main colours), thus, assuring and covering the developmental stages of diverse civilizations. This research shows the survey for the identification of natural dyes, procedures and techniques and their application. As for identification, we are not only limited by their technical and chemical significance, but also available information on their provenience, applications and the technologies involved (Santos, 2010).

Results

Table 1 – Identification of the natural dyeing sun stances studied (Santos, 2010).

Source of colorant	Part used	Colorant substance	Colour shades and mordants	Geographical location
Rubia tinctorum	Roots	Alizarin Purpurin (Anthraquinones)	Bright red (aluminium salts) Brown (aluminium and ferric salts)	Europe, Asia, Middle East
Acridocarpus Excelsus	Wood (bark)		Red (Without mordants)	Madagascar
Caesalpina echinata	Wood (bark)	Brasilin "Brasileína"	Orange (tin and aluminium salts) Brown(chromium and copper)	America (central e south, Asia (India, Sri-Lanka, Malaysia)
Bixa orellana	Seeds	Bixin Isobixin	Red Orange Dark yellow	America (central e south), Asia (Filipinas), Africa
Baphia nitida	Leafs Wood		Red Brown	Africa (Senegal, Gabon, Liberia, Serra Leona)
Reseda luteola	Seeds Superior branches	Luteolin (flavonoid)	Bright yellow Orange (aluminum salts) Green (ferric salts) Brown (chromium)	Asia, Europe, Northern Africa
Crocus sativa	Flower stigmas	"Crocetina" Crocin	Yellow (without mordants) Orange (without mordants)	East, Europe, Asia

Source of colorant	Part used	Colorant substance	Colour shades and mordants	Geographical location
Carthamus tintorius	Flower stigmas	"Cartamina"	Yellow (aluminium salts) Orange Red Rosa Brown (copper)	East, Asia, Europe (south) e Northern Africa
Chlorophora tinctoria	Wood	"Morina"	Yellow (without mordants) Orange (aluminium salts) Brownish red (chromium) Brown (copper)	America, Europe (South)
Alectra sessiliflora	Leafs Roots		Yellow	Africa, Asia
Isatis tinctorum Indigoferae	Leafs	Indigo	Blue (aluminum salts) Grey (copper or chromium)	Europe, China (temperate climate), Asia, America (central and south), Africa Sub-Saharan (tropical and subtropical areas)
Juglans regia	Wood (bark)	"Juglona" (naphthoquinone)	Brown Black (ferric salts)	East, Asia, Europe (south)
Acacia nilotica	Pods		Khaki-green Brown Grey or black (ferric salts)	Asia (India, Myanmar, Sri-Lanka), Africa (Senegal to Egypt e Mozambique e South Africa) Cape Verde, Jamaica, Nepal, Indonesia, Vietnam, Australia
Anogeissus leiocarpa	Leafs Roots	Gallic and Ellagic acid (Flavonoids)	Yellow Ochre Red Black (ferric salts)	Africa (Senegal, Ethiopia, Congo)
Barringtonia racemosa	Wood (bark) Roots		Brownish red Grey and black (ferric salts)	Africa (Somalia and South Africa), Asia tropical, Madagascar, Indic Islands, Micronesia, Polynesia, Australia (north)
Bruguiera gymnorhiza	Wood (bark)		Orange Brownish red Purple Grey Black (ferric salts)	Africa (central and south, Madagascar, Indic Islands, Tropical Asia, Australia (north), Micronesia, Polynesia
Haemotoxylon campechianum	Wood	Hematoxylin	Purple Violet Blue Black	America (central) e Europe

Source of colorant	Part used	Colorant substance	Colour shades and mordants	Geographical location
Roccela tinctoria	The whole lichen	Orcein	Red (tin salts) Violet (aluminium salts) Red, brown, blue, violet (on protein fibre, without mordants)	Atlantic coast, Europe
Arnebia hispidissima	Roots		Violet Purple (on silk)	Africa (Nigeria, Cameroons, Sudan), Egypt e Northern India
Kermococcus vermilis	Female insect on gestation	Kerminic acid	Red	Europe, East, Asia
Dactylopius coccus	Female insect on gestatio	Carminic acid	Red Violet Pink	America (central), Mediterranean (South Portugal, South Spain, Canarias Island)
Murex	Mollusc's glands	6.6' – dibromo-indigo	Pink Violet/purple Red	Europe, East, America (central and south)
Streptomyces coelicolor	Microorganisms		Blue	
Chomobacterium violaceum *Janthinobacterium lividum*	Microorganisms		Violet	
Monascus sp *Phaffia rhodozyma* *Micrococcus roseus* *Brevibacterium linens* *Bradyrhizobium sp* *Xanthomonas campestris*	Microorganisms		Yellow and red	

Discussion

The recent change in legislation concerning toxic dyes and the growing preference for natural substances by some consumers has led to the awakening interest in sources of natural dyeing compounds. Due to the current low usage of these particular natural dyes their prices remain high. To pursue an application on a large industrial scale, it will be vital to consider appropriate circumstances for the production of bio sources and its growth as well as innovative methodologies and sophisticated technologies tailored to the various requirements. It's also necessary to have a deeper knowledge of the biodiversity and its preservation.

When compared with synthetic dyes, natural ones present fewer complications concerning the ecosystem and consumers: biodegradability and non-toxicity. Although many companies don't attain credibility to these type of dyes (due to their alleged colour instability and industrial viability) new research suggest that its application conveys various benefits to the pursuit for new strategies of sustainable development. Such benefits include reducing the amount of non-renewable energy, water waste and pollution in general, mainly in an age where modern biotechnology (or other technologies like Sonic-dye) can be determined given its possibilities, efficiency and various applications (Vankar et al, 2008). One can also consider producing locally, where the resources exist, reducing transportation costs, creating jobs in small communities and benefiting from their know how. All these aspects may consequently result in cost reduction (on a long-term period) to the industry.

Etno Botany Colours is a line of natural dyes created from the union of Etno Brasil (natural dyes research), Grupo Centroflora (production of vegetal extracts) and Cognis Brasil, a company who enables advanced applications for this new line of coloured compounds. Besides the development of safe natural dyes (industrial application with low environmental impact), this cooperative aims to create selling alternatives for small producers and rural communities, establishing a network of sustainable raw materials. Allying environmental awareness and technology, Etno Botany Colours contributes to the creation of a whole new concept of the industrial usage of dyes, creating way for a responsible consumption attitude where waste and degradation gives place to the sustainable usage of biodiversity and quality of life. Within the fashion design industry these natural coloured substances are applied in the dying process of yarns, fabrics and knitwear, allying ecology and fashion design (Centroflora, 2008). This line of colorants is the result of substances extracted from the Brasilian fauna and flora (or species adapted to the territory) and represents an historical landmark to the economical, social and cultural context of the country.

Conclusion

The growing concern about environmental quality, the levels of toxicity of some of the synthetic dyes plus the usage of non-renewable resources (amongst other issues including legislation, textile effluents, harmful substances, etc.) has led to a gradual interest in the reintroduction of natural dyes into the fashion and textile design industries.

The sustainable use of the existing bio resources for the production of natural dyeing substances has become an alternative for the textile industry to minimise negative effects to the ecosystem and consumers. With a deeper knowledge and better understanding of plant, animal and micro organic species, we can obtain dyes that show great efficiency in colour fastness (in the dying process). It can also offer many colour shades satisfying consumer’s demands and industry necessities.

Benefiting from the acquaintance of existing (or yet to be explored) biodiversity and historical ancient dyes (and dyeing techniques), as well as indigenous populations expertise one can make use of classic biotechnology. Furthermore, with cutting edge technologies we can improve these dyes so that they are feasible within a larger scale befitting the purposes and demands of the fashion and textile design industry (genetic engineering, sonic dye technology etc.).

Sonic dye technology consists of an extreme bonding technique (it bonds the coloured substance to the fibre) allowing a better and improved colour fastness, which may help to establish an industrial reliance on bio dyes. It is the current practice within genetic engineering that allows for the existence of blue natural cotton fibres. This procedure completely cuts off the whole dyeing process including its water waste, energy and harmful textile effluents. Thus modern biotechnology will play a major role in these yet to come changes.

All the bio resources in this study represent a high genetic wealth that can be explored either through mass selection or through genealogies from crossing previously selected species. Nevertheless, the key question in this subject is on how to make these technologies available for all, including the production countries that continue to be sub developed as well as the most polluting ones. It is essential to understand how these countries can be drawn to these new technologies, and to assess the initial cost of their implementation, so that the companies grow interest and invest on innovation.

Acknowledgements

The authors would like to thank to FCT – Fundação para a Ciência e Tecnologia, SFRH/BD/80457/2011 for all the support as well as to CIAUD – Centro de Investigação em Arquitectura, Urbanismo e Design and to FAUTL – Faculdade de Arquitectura da Universidade Técnica de Lisboa.

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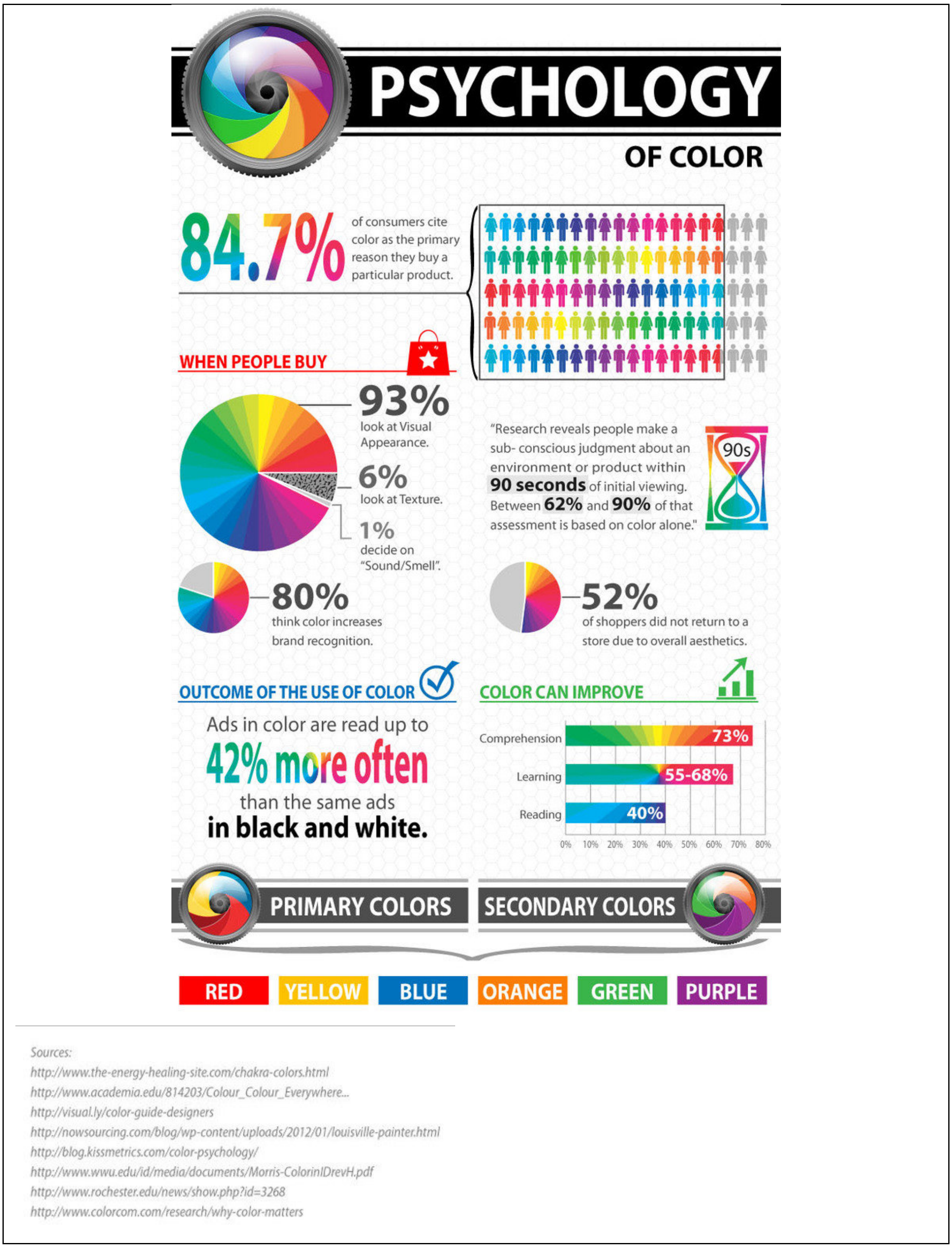
Appendix F. Curious general facts on the psychology of colour



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Appendix G. Natural dyes: Biological resources, Parts used, Geographical location

Dye source	Part used	Geographical location
Rubia tinctorum	Roots	Europe, Asia, Middle East
Acridocarpus Excelsus	Wood (bark)	Madagascar
Caesalpina echinata	Wood (bark)	America (central e south, Asia (India, Sri-Lanka, Malaysia)
Bixa orellana	Seeds	America (central e south), Asia (Filipinas), Africa
Baphia nitida	Leaves Wood	Africa (Senegal, Gabon, Liberia, Serra Leona)
Reseda luteola	Seeds Superior branches	Asia, Europe, Northern Africa
Crocus sativa	Flower stigmas	East, Europe, Asia
Carthamus tintorius	Flower stigmas	East, Asia, Europe (south) e Northern Africa
Chlorophora tinctoria	Wood	America, Europe (South)
Alectra sessiliflora	Leaves Roots	Africa, Asia
Isatis tinctorum; ***Indigoferae***	Leaves	Europe, China (temperate climate), Asia, America (central and south), Africa Sub-Saharan (tropical and subtropical areas)
Juglans regia	Wood (bark)	East, Asia, Europe (south)
Acacia nilotica	Pods	Asia (India, Myanmar, Sri-Lanka), Africa (Senegal to Egypt, Mozambique, South Africa) Cape Verde, Jamaica, Nepal, Indonesia, Vietnam, Australia
Anogeissus leiocarpa	Leaves Roots	Africa (Senegal, Ethiopia, Congo)
Barringtonia racemosa	Wood (bark) Roots	Africa (Somalia and South Africa), Asia tropical, Madagascar, Indic Islands, Micronesia, Polynesia, Australia (north)

Bruguiera gymnorhiza	Wood (bark)	Africa (central and south, Madagascar, Indic Islands, Tropical Asia, Australia (north), Micronesia, Polynesia
Haemotoxylon campechianum	Wood	America (central), Europe
Roccela tinctoria	The whole lichen	Atlantic coast, Europe
Arnebia hispidissima	Roots	Africa (Nigeria, Cameroons, Sudan), Egypt, Northern India
Kermococcus vermilis	Female insect on gestation	Europe, East, Asia
Dactylopius coccus	Female insect on gestation	America (central), Mediterranean (South Portugal, South Spain, Canarias Island)
Murex	Mollusc's glands	Europe, East, America (central and south)
Streptomyces coelicolor	Microorganisms	
Chomobacterium violaceum Janthinobacterium lividum	Microorganisms	
Monascus sp; Phaffia rhodozyma; Micrococcus roseus; Brevibacterium linens; Bradyrhizobium sp; Xanthomonas campestris;	Microorganisms	

Reference:

Santos, GC (2010), *Corantes texteis naturais: a Biotechnologia da antiguidade ao século XXI*. Dissertação de Mestrado, Universidade Técnica de Lisboa, Faculdade de Arquitectura

Appendix H. Natural dyes: Biological resources, Chemical substances and colour shades

Dye source	Chemical substance	Colour Shades (**mordants**)
Rubia tinctorum	Alizarin Purpurin (Anthraquinones)	Bright red (aluminium salts) Brown (aluminium and ferric salts)
Acridocarpus Excelsus		Red (Without mordants)
Caesalpina echinata	Brasilin	Orange (tin and aluminium salts) Brown (chromium and copper)
Bixa orellana	Bixin Isobixin	Red Orange Dark yellow
Baphia nitida		Red Brown
Reseda luteola	Luteolin (flavonoid)	Bright yellow Orange (aluminum salts) Green (ferric salts) Brown (chromium)
Crocus sativa	Crocetin Crocin	Yellow (without mordants) Orange (without mordants)
Carthamus tintorius	Cartamin	Yellow (aluminium salts) Orange Red Rosa Brown (copper)
Chlorophora tinctoria	Morin	Yellow (without mordants) Orange (aluminium salts) Brownish red (chromium) Brown (copper)
Alectra sessiliflora		Yellow
Isatis tinctorum; Indigoferae	Indigo	Blue (aluminum salts) Grey (copper or chromium)
Juglans regia	Juglon (naphthoquinone)	Brown Black (ferric salts)
Acacia nilotica		Khaki-green Brown Grey or black (ferric salts)
Anogeissus leiocarpa	Gallic and Ellagic acid (Flavonoids)	Yellow Ochre Red Black (ferric salts)
Barringtonia racemosa		Brownish red Grey and black (ferric salts)

Bruguiera gymnorhiza		Orange
Haemotoxylon campechianum	Hematoxylin	Purple Violet Blue Black
Roccela tinctoria	Orcein	Red (tin salts) Violet (aluminium salts) Red, brown, blue, violet (on protein fibre, without mordents)
Arnebia hispidissima		Violet Purple (on silk)
Kermococcus vermilis	Kermesic acid	Red
Dactylopius coccus	Carminic acid	Red Violet Pink
Murex	6.6' – dibromo-indigo	Pink Violet/purple Red
Streptomyces coelicolor		Blue
Chomobacterium violaceum; Janthinobacterium lividum		Violet
Monascus sp; Phaffia rhodozyma; Micrococcus roseus; Brevibacterium linens; Bradyrhizobium sp; Xanthomonas campestris		Yellow and red

Reference:

Santos, GC (2010), *Corantes texteis naturais: a Biotechnologia da antiguidade ao século XXI*. Dissertação de Mestrado, Universidade Técnica de Lisboa, Faculdade de Arquitectura

Appendix I. Evaluation of the dyeing properties of *Lycopene* dye on polyester fibre using disperse dyeing

Evaluation of dyeing properties of *Lycopene* dye on polyester substrate (optimised disperse dyeing)

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ABSTRACT

Colour has always been important in the social and economical context of mankind. It is one of the most important aspects of fashion and textiles, with a long history and remarkable evolution. Dyeing process effectiveness is, therefore, crucial to the textile industry success, attentive on how colours influence consumers. Nevertheless, dyeing methods are often associated with water waste, fossil fuel generated energy, toxicity and contamination, posing a serious threat to the environment and human health. Certain synthetic coloured substances are regarded as toxic and pollutant leading consumers to question textile products' sustainability. The search for natural coloured substances is increasingly intensifying, as these are perceived as being compatible to nature and less toxic to consumers and the ecosystem. Sophisticated technologies such as synthetic biology plays a crucial role in the development of dyes capable of meeting consumer's demands as well as this new century's requirements. In this study we explore the dyeing properties of a class of carotenoid - *Lycopene* - usually used in the food industry as a red colorant that has been recently synthesised through bacteria. The colouring ability of *Lycopene* dye has been tested on polyester substrate and found to be suitable for textile dyeing.

1. INTRODUCTION

1.1 Sustainability in the textile industry

Never before apparel industry has lived such a fast pace period. Brands, collections, colours and styles are increasingly being created every season, changing accordingly to the many trends society generates. People and lifestyle transforms rapidly, and so their expectations. With all the demanding adjustments this sector has to currently face, it seems, though, the concept of clothing remains the same for the past centuries; textiles are still attached to old ways of thinking materials and dated methods of production and application revealing reluctance to dramatic changes and radical innovation within the sector.

Sustainable materials integrating technologies, environment, communities, people, language and culture that will inevitably emerge as products are still seen as a challengei. Textiles' world is vast and varied with many raw materials and techniques employed. It is one of the most pollutants sectors, contributing a great deal to the environmental impact, poor working conditions, energy and water waste, contamination, etc. It is crucial the focus on how to reduce the textile production environmental footprint and the consideration on how materials can allow for a more sustainable future, whilst, simultaneously, promoting and enhancing wellbeing and influencing lifestyle[ii].

Consumers are increasingly aware of textiles industry's hazards and demand for quality products, planned accordingly to their function, lifecycle and produced within eco-friendlier methods. The apparel industry is more than style and excitement; consumers expect colour and change allied to quality and function. Not only are they attentive to material's quality, provenience, production processes and the friendliness of these methods but they also question their function, how these products change over time accordingly to people's lifestyle, adapting to expected changes as one travels, ages, transforms, experiences, cease to consume, etc. Most concepts are closely related to the life span of a product.

As science evolves from archaic technologies to more sophisticated ones also new tools start to emerge. Sustainable strategies to reduce environmental impact find in biotechnology an infinite number of applications and it has been widely used since a few decades, mainly dealing with clean technologies[iii]. The use of bio resources as a technology is millenary but as a scientific subject it took only the usage of new tools to discover different uses and functions of plants, animals, or microorganisms thus allowing for the improvement of this new field of human knowledge[iv]. Biotechnology was always applied, since ancient times, in textiles, from the production of fibres and dyes or management of residual waste. From classic biotechnology to modern biotechnology, its evolution takes place through significant advances in genetic engineering and synthetic biology where the use of living organisms is seen as a biological process that may replace industrial or mechanical systems. Sometimes introducing visionary and radical strategies for improving the performance of objects around, its multiple applications are focused and designed to deal with sustainable development of materials and core industrial issues[v].

Sustainable design seeks innovation within the sector. Science is being introduced as a methodology in the creative process that slowly embraces different technologies, social improvement, environment and wellbeing, whilst projecting products.

1.1.1 Sustainable materials: dyes

Textiles and fashion industry's negative impacts on the entire ecosystem are varied: spinning, weaving and industrial production is associated with non renewable energy and waste; finishing processes, as dyeing and printing, consume vast amounts of water and chemicals, releasing numerous volatile agents into the environment[vi]. Dyeing has always been, throughout the centuries, one of the most important industries with a remarkable evolution. Coloured compounds' production is, thus, an indispensable process within the textile industry effectiveness.

Colour was always of a major importance for mankind, playing crucial roles in both the social and economical contexts. Related to different aspects of human behaviour, symbolism and aesthetics, colour is known to influence people in many levels such as emotional[vii]or shape perception[viii]; it is known to influence hormones, blood pressure and body temperature[ix]. As an influence agent, it is particularly crucial to the commercial success of fashion and textile products and apparel industry explores this aspect in great detail.

Besides print and pattern, consumers demand for basic characteristics in textiles. These must resist to the agents that cause colours to fade (washing, light, perspiration, etc.). To guarantee these properties, dyes conferring colour to fibres must present high-affinity properties with the latter, allowing for a greater colour fastness and uniformity. They must, simultaneously, allow for a great range of colour shades and be cost effective. The high number of existing synthetic dyes is justified given the requirements of industry and consumers as well as the quantity and characteristics of the fibres, which require dyes with specific features. Despite their many advantages, some synthetics dyes or dyeing methods are regarded as little sustainable partly due to effluents associated to these finishing processes, that, if not conveniently treated, can be harmful to the environment and human healthx,xi,xii,xiii. The use of several synthetic dyes by consumers carries severe risks that are associated with the length of time of exposure to it, oral ingestion, skin and respiratory tract susceptibility5.

Consumer's expectations and inevitable issues related to sustainability within this industry such as energy waste, contamination, climate, environment and lifecycle of a product have triggered a preference for organic materials. This has also led to the gradual interest and reintroduction of natural dyes (generally used in ancient times, mostly derived from plants) in the market. These bioresourced dyes possess a biodegradable nature and are, generally, considered safer. They possess a higher level of affinity with the environment causing less impact. Depending on the natural dye, some are known to possess great colourfastness properties (applied with or without mordents), fair range of colours, protection properties against UVR8 as well as medical properties as antimicrobial9,10 and anti-inflammatory advantages11.

Despite the vast array of coloured compounds found in nature, only a small parcel of it is applied to textiles. An extensive amount of data got lost at the time of the introduction of synthetic dyes in the market and most knowledge on resources, extraction techniques and applying methods is limited. Deeper understanding on materials - dyes and fibres – and the biodiversity yet to be explored is required. Dyeing with natural dyes tends to be, simultaneously, expensive due to their rather complex processes of extraction and application and the very limited amount of dyestuff provided. Knowledge on bio sources, and their different properties, is vital to push boundaries on applicable research within the sector.

Technologies using bio resources are not new but their evolution is rapidly transforming the world with their infinite number of possibilities. Furthermore, the scope of science allows, currently, for a completely new radical way of rethink materials that will emerge as products around us.

Regarding dyes, state of the art technologies consist in the production of coloured compounds by microorganisms. Dyes produced by this type of bio sources are created through a mechanism that uses living bacteria, often found in different plants' microsystems (rhizosphere), manipulating at times their environment. This living machine might be considered as a sustainable design strategy for mass manufacture. Its effectiveness finds in synthetic biology a way to enable the production of specific dyes designed to meet the industry's demands and consumer's expectation. Microorganisms can, not only grow fast but also, be programmed to provide varied dyes with different properties and different colours, being simultaneously cost effective.

Some pigments created through bio machines were already isolated in lab. "E-chromi" is one of such projects, born from the collaboration of scientists and designers who genetically engineered bacteria to secrete a variety of coloured pigments, visible to the naked eye. Standardised sequences of DNA (biobricks) were designed and inserted into E.coli bacteria enabling for the production of colours such as red, yellow, green, blue or violet, possibly allowing for its application on textiles. One of the isolated pigments is Lycopene, a red shade compound found in tomato fruit. To understand if this type of dye can be scaled up for industry, experiments onto different substrates must be conducted.

Lycopene (figure 1), extracted from fruits of Solanum lycopersium plants, is a known carotenoid pigment representing something around 65% to 98% of its content12. It is found in tomatoes and applied, commonly, as a natural red food colorant and a nutraceutical13. Its beneficial and therapeutic properties are well documented and established. It is a powerful antioxidant - the stronger amongst all class of carotenoids - and studies suggest lycopene is effective in varied medical preventive treatments14. Its varied medicinal properties are analysed and documented in many recent studies15,16,17,18.

Although many studies were conducted on the advantages and properties of natural dyes regarding dyeing procedures, colour shades and fastness properties, no information is found on Lycopene and its interaction with textiles. For the first time, this project considers the application of lycopene dye to textiles. We conducted the present study to investigate the dyeing and fastness properties of polyester using lycopene pigment. Dyeing conditions such as the concentration of the dye, dye bath pH, dyeing temperature, dyeing time and the overall fastness properties were investigated.

2. EXPERIMENTAL

2.1 Materials

2.1.1 Dye material

Lycopene natural food colorant, obtained from LYCORED COLORS (figure 1).

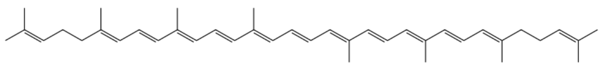


Figure 1: Chemical structure of Lycopene

2.1.2 Fabric

Polyester fabric (Polyester Sateen Glacier White) was obtained from Whaleys (Bradford) LTD. Harris Court, Great Horton, Bradford, West Yorkshire, BD7 4EQ England.

2.2 Method

2.2.1 Dyeing procedure

Lycopene was tested to understand its dyeing properties in Polyester fabric. Lycopene dye is a non-water-soluble dye therefore oxidising and levelling agents were used (2g dm-3 Ludigol AR + 1g dm-3 Levagol DLP) in the dye bath.

Fabric was cut into 5g square samples that were dyed with 0.5%, 1%, 2%, 5% omf. These samples were dyed at a liquor ratio of 30:1, with the dye bath being maintained at pH value 4.5 (sodium acetate $C_2H_3NaO_2$ and acetic acid $C_2H_4O_2$ solution). The temperature was raised up to 140 °C and held at this level for 60min. Fabrics were removed and rinsed with water and put to dry at room temperature. Reduction clearing to remove any surface deposited dyestuff followed in a Sodium carbonate (1.5g dm-3 Na_2CO_3) and Sodium dithionite (2g dm-3 $Na_2S_2O_4$) solution, at a liquor ratio of 20:1, for 15min. at 60°C.

Other sets of samples followed in order to understand their quality regarding colour depth and shades of the dyeing. To determine colour uniformity different parameters were applied to the speed rotation and to the temperature rising speed while increasing up to 140ºC as shown in Table 1.

Table 1

Dyeing parameters.

Samples	Dyeing temperature	Dyeing speed rotation
Set I	2ºC/min. up to 60ºC - 4ºC/min. up to 140ºC	35
Set II	7ºC/min. up to 140ºC	20
Set III	7ºC/min. up to 140ºC	10

2.2.2 UV–visible spectrometric analysis

Visible Absorption spectra were recorded using an UV Jasco V-630 model spectrophotometer. Results can be analysed in table 4.

2.2.3 Colour strength and colour depth measurements

The colour strength and colour depth of dyed samples were determined colourimetrically using K/S Sprectraflash SF600 Plus-CT Datacolor model. The update of dye results can be observed in table 2.

2.2.4 Determination of fastness

Wash fastness tests were carried using a specimen of dyed fabric in contact with a multifibre strip. These were inserted into tubes containing a solution of reference detergent and water. These were agitated for 30 min. at 40º C temperature. The change in colour of the specimen and the staining of the adjacent fibres were assessed with the reference of the original fabric sample, using the Grey Scale.

3. RESULTS AND DISCUSSION

3.1 Effect of dye concentration

Experiments were carried out to find the effect of the amount of dye used onto the polyester fibre. As shown in Figures 1, 2, and 3, the K/S values rise with the increase in dye concentration. Set of dyeing I presents higher K/S values when compared to sets II and III.

3.2 Effect of speed rotation and temperature

The experiments carried out onto polyester substrate show the potentiality of Lycopene application as a natural textile dye. By observing the different shades of orange provided and results in table 1, colour intensity is higher at 5% concentration of dye when the dyeing temperature was increased at a slower rate (2ºC/min. up to 60ºC and 4ºC/min. until 140ºC) and rotating at a higher speed (35), with shades differing exponentially in colour, when compared to other parameters (7ºC/min. increasing up to 140ºC at rotation speed of 10 and 20), displaying weaker colour intensities as shown in table 2.

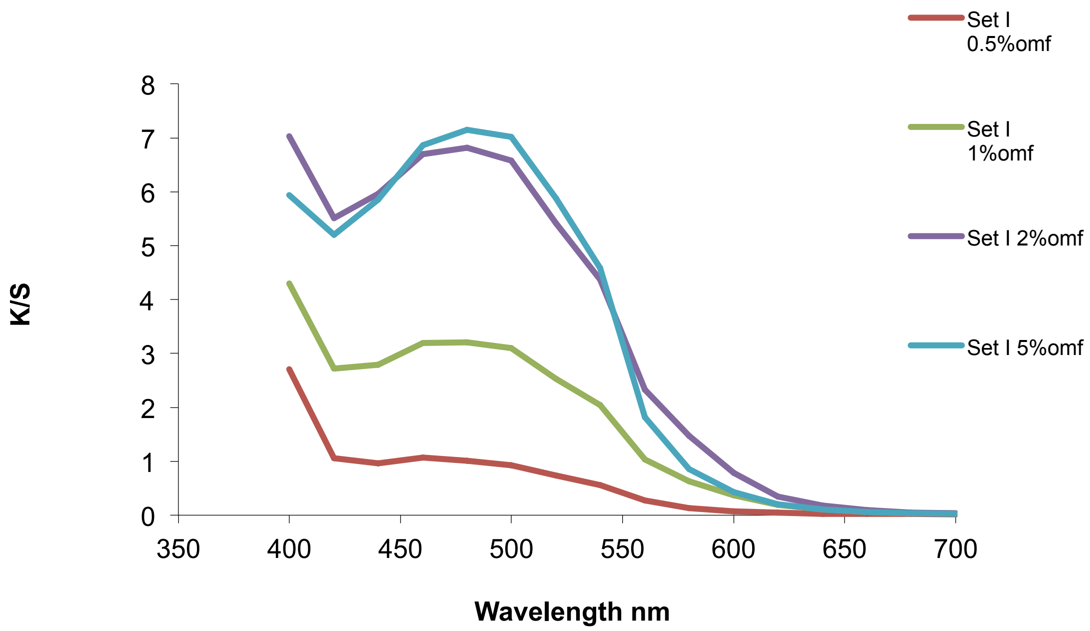


Fig. 1. K/S values of different percentages of on mass of fibre, set of dyeing I.

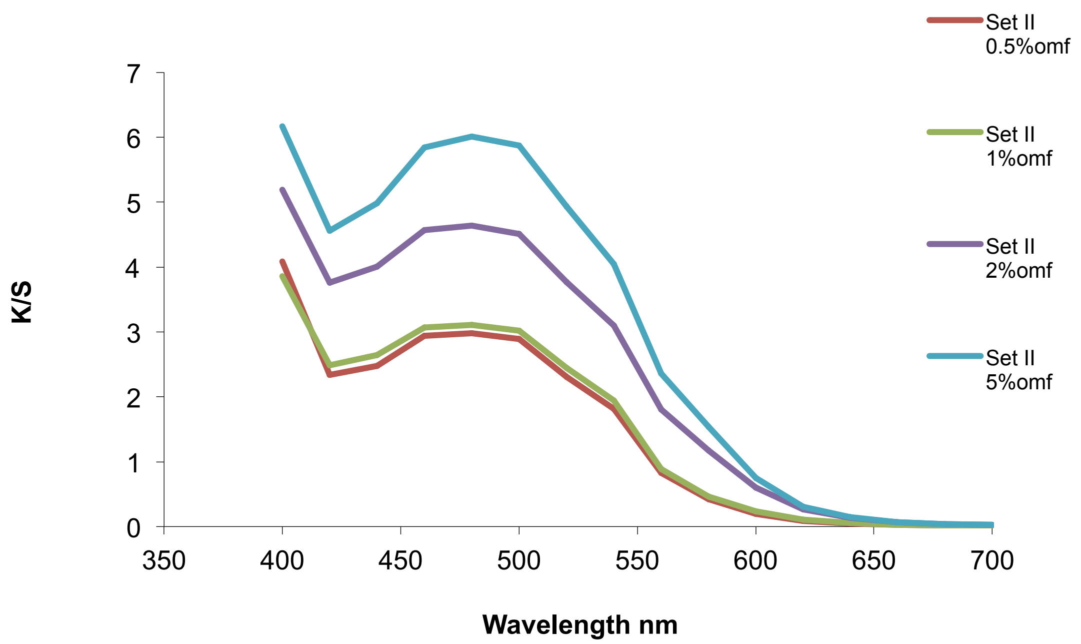


Fig. 2. K/S values of different percentages of on mass of fibre, set of dyeing II.

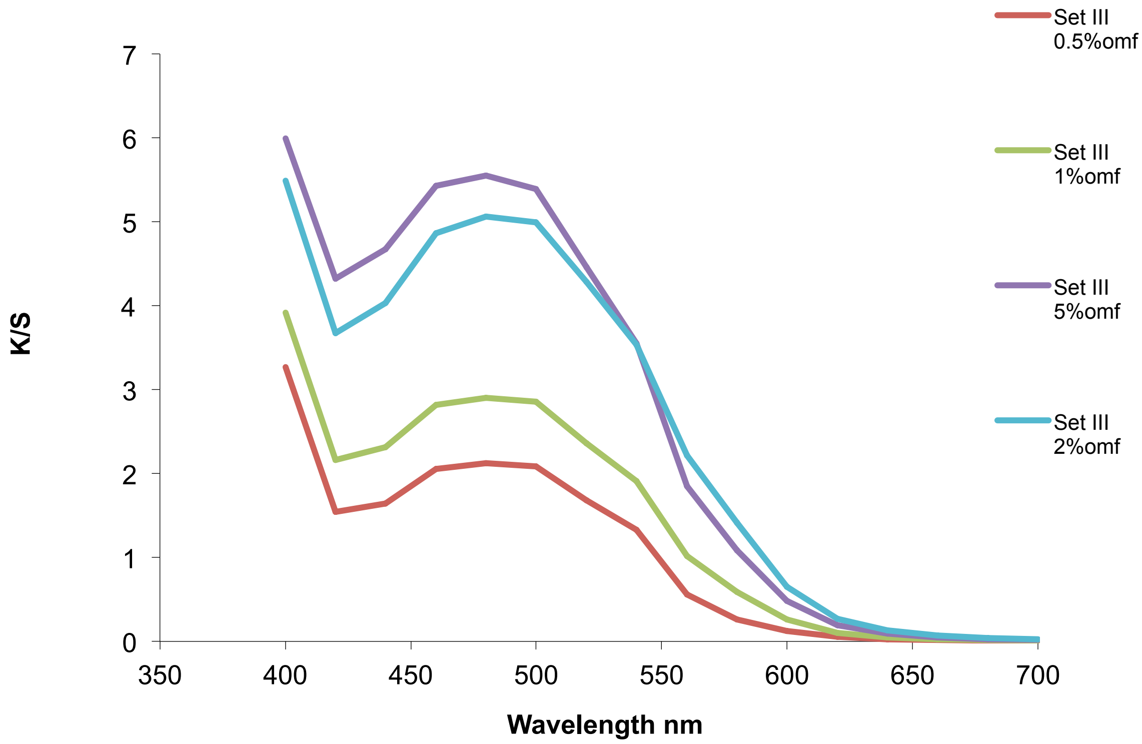


Fig. 3. K/S values of different percentages of on mass of fibre, set of dyeing III.

Table 2

K/S values.

Samples	Set I		Set II		Set III	
% on mass of fibre	Max	K/S	Max	K/S	Max	K/S
0.5%	460	1.069	460	2.937	460	2.057
1%	460	3.190	460	3.065	460	2.819
2%	460	6.698	460	4.568	460	4.867
5%	460	6.868	460	5.846	460	5.427

Table 3

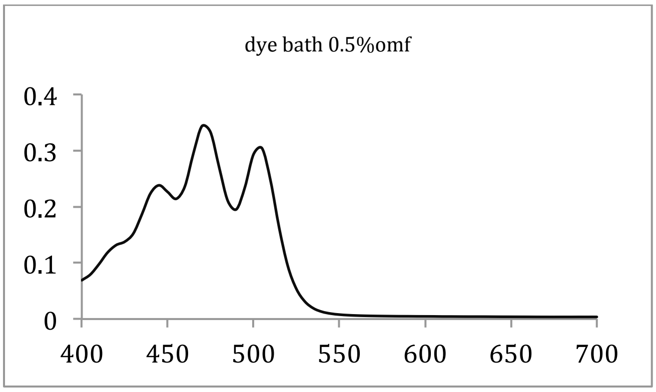
K/S values after light exposure.

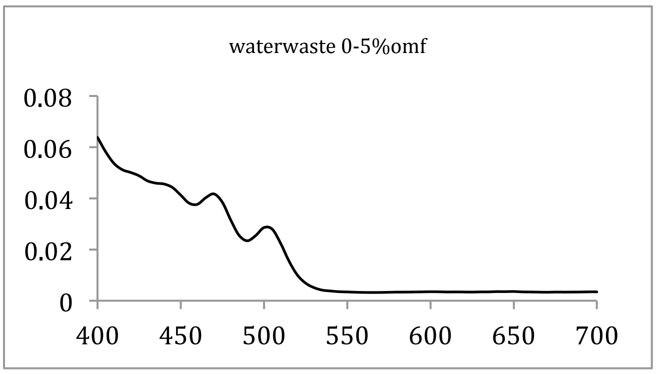
Samples	Set I		Set II		Set III	
% on mass of fibre	Max	K/S	Max	K/S	Max	K/S
0.5%	460	1.024	460	2.259	460	1.748
1%	460	3.067	460	2.077	460	2.068
2%	460	3.896	460	2.562	460	2.873
5%	460	6.323	460	2.991	460	3.507

3.3 UV-Visible spectroscopy study

The absorbance spectra of dye bath and wastewater solutions of dyeing with Lycopene are shown in Fig. 4. From this figure, the shape of initial dyeing bath's absorbance spectra differs from the wastewater solution. The lowest absorbance values regards Dyeing 0.5% which shows that most of the dye was bond to the fibre and is therefore the sufficient amount of dye for the amount fibre in use.

As shown in table 4, Dyeing 5%omf represent the highest absorbance values meaning there is a waste of dye; most of the dye concentration did not get fix to the fibre. The percentage of omf is way higher for the amount of fabric.





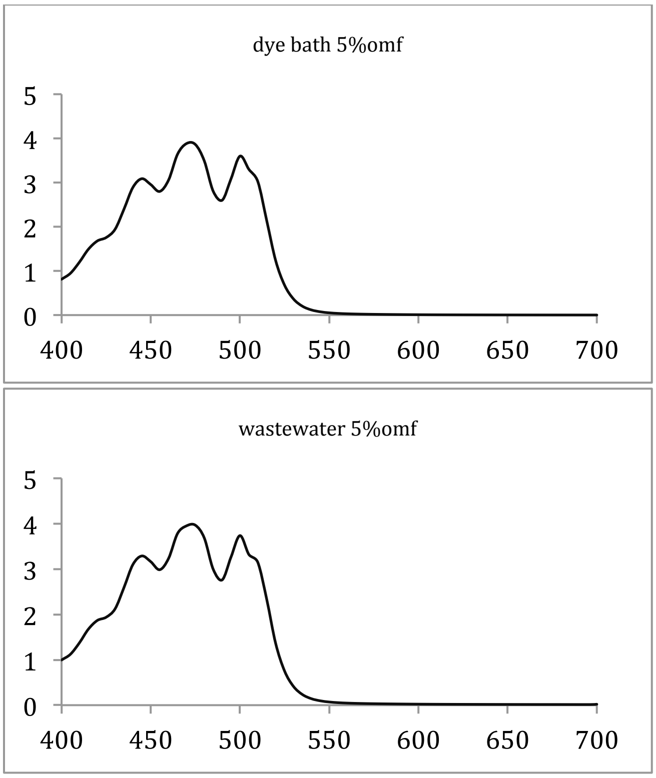


Fig. 4. The absorbance spectra of dye bath and wastewater solutions (set I); 0.5%omf & 5%omf.

Table 4

UV-Visible spectrophotometer values.

Samples	Set I – Dye bath		Set I – After wash	
% on mass of fibre	Max	K/S	Max	K/S
0.5%	470	0.344	470	0.042
1%	470	0.683	470	0.058
2%	470	3.612	470	3.675
5%	470	3.882	470	3.951

3.4 Fastness properties

Fastness properties of dyed fabrics are shown in Table 5. Results indicate good colourfastness properties of overall dyed samples, displaying no colour staining and little colour changing.

Table 5

Colour fastness of samples.

Samples % omf	Washing fastness	Staining of wool	Staining of acrylic	Staining of polyester	Staining of polyamide	Staining of cotton	Staining of diacetate
Set I-0.5%	4/5	5	5	5	5	5	5
Set I-1%	4	5	5	5	5	5	5
Set I-2%	4	5	5	5	5	5	5
Set I-5%	4	5	5	5	5	5	5
Set II-0.5%	4/5	5	5	5	5	5	5
Set II-1%	4	5	5	5	5	5	5
Set II-2%	4	5	5	5	5	5	5
Set II-5%	3	5	5	5	5	5	5
Set III-0.5%	4/5	5	5	5	5	5	5
Set III-1%	4	5	5	5	5	5	5
Set III-2%	4	5	5	5	5	5	5
Set III-5%	3	5	5	5	5	5	5

3.4 Environmental and economical benefits

This dyeing process involves a natural dye, non-toxic and nutritious nature, highly suitable for health sensitive application. There is no environmental risk as it is biodegradable. Since it can be synthesised by bacteria there is an economical aspect to consider as we can skip the, usually, difficult processes involving natural dyes’ extraction and production, saving related energy consumption.

4. CONCLUSIONS

It is a challenging period for the textile industry, with the economic downturn threatening sales and a growing awareness of real social and environmental challenges, such as climate change, wars over resources and increasing consumer's expectations of brands.

Biotechnology's evolution takes place through significant advances in genetic engineering and synthetic biology discovering uncommon uses and functions of plants, animals or microorganisms, sometimes even replacing old industrial mechanical systems to biological ones.

The appropriation of biotechnologies exerts increasing influence in our daily lives. Technological innovation and breakthroughs in textiles are establish to meet a variety of objectives as improvement of varied species of plants used in the manufacture of fibres or their properties, production of new types of fibres, different types of dyes, effluents' management, amongst others. The recent trend of extensive use of biomaterials in product and fashion garments is growing exponentially and offers perspectives on sustainable design that assimilates science and technology, sustainable strategy and wellbeing and social innovation. Textile and fashion designers are looking at science as a tool to be used as part of the creative process allying, simultaneously, cut edge and complex technologies to serve better apparel industry in terms of quality innovative garments, increasingly trying to create textiles which lifecycle enable to adapt accordingly to the consumer's characteristics and inevitable changes - age, shape, taste, needs, etc.

Natural dyes obtained through engineered bacteria may contribute to a more ecological process to produce natural dyes and may fill the gap regarding their limited quantity (or extraction difficulties) providing feasibility and application on an industrial level. On the other hand, natural dyeing compounds, as Lycopene, are more biodegradable and safer (applied to textiles offer garments medicinal properties.)

This is the first report where Lycopene was applied to textiles. In our study, Lycopene was used to dye polyester. The obtained results suggest that the colorant extracted from fruits of Solanum lycopersium plants can be considered a potential source of natural textile dye.

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